**A Quasi-Optical Electron
Cyclotron Maser for
Fusion Reactor Heating
Final Report**

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1 Introduction

1.1 Background

High power microwave and millimeter sources, such as the quasi-optical electron cyclotron maser (QOECM) are important in fusion research[1] [2], as well as in high-energy physics[3] and in other applications. The interaction between the electromagnetic modes of a Fabry-Perot resonator and an electron beam gyrating through a magnetic field has been studied for both the cases of beams parallel and perpendicular to the resonator. The parallel case was theoretically first studied by Kurin for forward and backward wave interaction[4], and experimentally by Korolev and Kurin[5]. Kreischer and Temkin[2] reviewed the general case of the linear small signal interaction parallel and perpendicular to the resonator. Sprangle, *et al*[6] [7] discussed the perpendicular case in a self-consistent linear and nonlinear theoretical study using the Gaussian transverse profile of an open resonator with a single longitudinal mode. Experimental verification of the devices operation was first mentioned in work at the Naval Research Laboratory[8]. Theoretical studies using a time-dependent analysis of a large number of longitudinal modes with similar transverse mode profiles have demonstrated that single longitudinal-mode operation can be achieved at equilibrium and that performance can be enhanced by pre-bunching the electron beam and tapering the magnetic field[9]. The use of output coupling apertures in the mirrors has been studied theoretically in relation to the structure of the modes for both confocal and nonconfocal resonators by Perrenoud[10]; use of an open resonator with stepped mirrors has been studied in order to choose a particular longitudinal mode[11]. Studies at the Naval Research Laboratory mirror used configurations that diffraction couple the energy from around the mirror edges, so that the transverse profile inside the resonator can be selective to the fundamental mode[12].

1.2 Research Overview

At the University of California, Berkeley, quasi-optical electron cyclotron masers with various output coupling apertures have been studied at 28Ghz[13] [14]. In current research, large radius mirrors are used to provide the high Q values required for efficient electromagnetic interaction with the electron

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beam and to reduce the diffraction losses. A coupling structure is designed to deliver the output radiation about the axis of the mirrors. The configuration is shown in Fig. 1. Fig. 1(a) shows a Cassegrain arrangement. In comparison, Fig. 1(b) shows a coupling mirror that has been made smaller than the output aperture in the secondary mirror, so that energy is coupled from around the mirror edge. The perturbation of the coupling structure selects a preferential mode for the operation of the quasi-optical device. This corresponds to a superposition of transverse modes. A microwave bench is used to examine the Q of the resonator, the frequency modes of excitation, and the profile of the output radiation. The resonator is tested using a high power pulsed electron beam in order to study its interaction properties.

2 Experimental Set-up

The experimental arrangement is displayed in Fig. 2. Water-cooled copper Helmholtz coils produce a near uniform static field of up to 10kG perpendicular to the axis of the resonator. The field strength is measured by monitoring the voltage across a shunt to the coil current. A secondary coil is used to produce a magnetic field at the electron gun. An iron collar is placed around the area of the gun cathode. The magnet set has a 23cm bore, allowing a cylindrical vacuum tank to fit concentrically. A 2.5cm cylindrical waveguide is placed in the spacing separating the Helmholtz pair for the RF output to leave the magnetic field in the radial direction. A horn is used as a transition from the waveguide to the half-wavelength thickness 5cm diameter output window. An oil diffusion pump with a liquid nitrogen cold trap maintains the background vacuum pressure to below 1×10^{-7} torr as measured by an ionization gauge.

A pair of self-synchronous motors remotely drives both the passive mirror and the coupling mirror in order to give each a variation of approximately 2.5cm in translation. The 5cm mirror is attached to the transition end of a copper tube that serves as an overmoded waveguide and connects to the motor drive outside the vacuum chamber. The attaching transition is a slow 5cm dual slice into the waveguide, ending in a small thickness weld to the 5cm mirror. A double bellows arrangement allows for the output window to remain fixed, eliminating the mechanical difficulties of driving the mirror against the pull of

the vacuum and maintaining a fixed distance between the coupling horn to the detector.

The electron gun for this experiment consists of a magnetron injection gun manufactured by Varian. The external solenoid provides a uniform axial magnetic field about the cathode. The strength of the field is limited by an iron collar flux conserver. The cathode is heated by an AC source. The electrons are emitted almost radially with a slight inclination due to the shape of the cathode, providing for an initial axial drift. The acceleration potential of the anode causes an axial acceleration. As the electrons move toward higher magnetic fields the perpendicular kinetic energy increases according to the conservation of the adiabatic invariant W/B , where W is the perpendicular kinetic energy. This provides for the necessary pitch angles for efficient energy transfer of beam energy to the resonator. The gun provides an annular electron beam with a diameter of 6.0mm at the resonator. The pitch angle of the electron beam is approximately 2-3 in the magnet set. The electron beam operates at energies of up to 80keV and at currents of up to 12A in pulsed operation.

The photon drag detector serves as the main power diagnostic. The detector has a nanosecond rise time so that measurements can be made along the time scale of the pulse. The response in voltage for a given RF intensity is derived by Verboncoeur[15]. A 2.5cm cylindrical block of n-type silicon is placed in a long cylindrical waveguide of the same radius. A matching horn couples the microwave beam from the maser output window. By means of the photon drag effect, the microwave intensity induces a proportional voltage difference across the two faces of the silicon block. This voltage response is then amplified and monitored. A static water calorimeter and a crystal diode detector are also used.

3 Analysis

3.1 Theoretical Model

To calculate the theoretical efficiencies of the interaction, we follow Sprangle, *et al*[6], generalizing the transverse electric field mode to one that is appropriate for our resonator configuration. The electron beam is assumed to be uniform and having a minimal spread in velocity, although the electrons are randomly distributed in phase. Interactions between electrons are not taken in consideration, so that

single-particle orbit equations are used. The Larmor radius is much smaller than the wavelength such that the electric field that the individual electron experiences changes only in the direction parallel to the magnetic field. The momentum in the z-direction is a constant of the motion. The transverse momentum is expressed as a superposition of gyration motion and a small drift motion. The important component of the RF field is considered to be the transverse electric field. The cavity operates in a single longitudinal mode. The gyration frequency of the electrons is tuned to the oscillation frequency with a small mismatch such that the electrons will bunch in phase. With these approximations the individual electron equations of motions describing the evolution of the perpendicular momentum and the phase angle θ can be expressed in terms of the variables for transverse position, the electric field, the frequency mismatch Δ , and the momentum. The procedure varies Δ to optimize efficiency of energy transfer for the beam for a given E. The final E is determined by an energy balance so that the total energy lost by the beam equals the energy loss by the resonator mode. The drift momentum variables can be seen to be small compared to the gyration momentum in the case where E/B is small. If the location of the gyration centers along the longitudinal profile is included in the field profile, then the equations of motion become[6]:

$$\frac{dp_{\theta}}{dz} = -\frac{eE\gamma m_0}{2p_{t0}} \cos \theta \quad (1)$$

$$\frac{d\theta}{dz} = \frac{(\Omega_0 - \gamma\omega)m_0}{p_{t0}} - \frac{eE\gamma m_0}{2p_{t0}p_{\theta}} \sin \theta \quad (2)$$

where E is the electric field profile in the z-direction and incorporates the longitudinal sinusoidal standing wave envelope, $\Omega_0 = eB_0/m_0c$ is the nonrelativistic electron cyclotron frequency, ω is the radiation frequency, and γ is the usual relativistic factor. These equations can be condensed for computation. The individual electron equations of motion describing the evolution of the perpendicular momentum and the phase angle θ can be expressed in terms of the variables for transverse position, the electric field, the frequency mismatch Δ , and the momentum. Let

$$t = \frac{\Omega_0 m_0 z}{2p_{t0}}, E_B = \frac{E}{B_0}, \Delta = \frac{\omega}{\Omega_0}, P = \frac{p_0}{m_0 c} \quad (3)$$

Then

$$\frac{dP}{dt} = -\gamma E_B \cos \theta \quad (4)$$

$$\frac{d\theta}{dt} = (1 - \gamma \Delta) + \frac{\gamma E_B}{P} \sin \theta \quad (5)$$

This gives us a set of equations in which there are two parameters, E_B and Δ , which are not determined by the initial conditions. As before, the final E is determined by an energy balance so that the total energy lost by the beam equals the energy lost by the resonator mode. We use in our initial conditions a uniform distribution among a sample of 20 particles in phase and average over the results for different electric fields for the efficiency. The procedure varies Δ to optimize the efficiency of energy transfer for the beam,

$$\eta_e = \left\langle \frac{K^f - K^i}{K^i} \right\rangle_{\theta_0} \quad (6)$$

for a given E_B , where K^i and K^f are the initial and final beam energies and $\langle \dots \rangle$ denotes an average. E_B is in turn determined by the balance of energy losses within the system. In the steady state the losses of the resonator must equal the gain from the radiation of the electron beam. Hence (as a conversion to mks units is made),

$$\eta_e K^i = \frac{T}{4\mu_0} \int_A \text{Re}(\vec{E} \times \vec{B}^*) dA \quad (7)$$

$$\eta_e K^i = \frac{\pi T}{2\mu_0 c} \int_0^\infty E^2 r dr \quad (8)$$

Note that η_e is a function of the electric field. It is then possible to find a value for the electric field that satisfies this equation for steady state operation. The total efficiency is the product of the electronic and transmission efficiencies,

$$\eta = \eta_e \eta_{trans} \quad (9)$$

The threshold condition for the start of oscillations is given by the power balance:

$$\eta I_b V \geq \omega E_{stored} / Q \quad (10)$$

where E_{stored} is the energy stored in the resonator and the expression for Q is used. In the case of the steady state oscillations this can be reformulated as an expression for I :

$$\eta Q I_b = \omega E_{stored} / V \quad (11)$$

For small coupling the efficiencies can be compared with the linearization of the equations above. If the assumption is made that the electrons are evenly distributed over the longitudinal standing wave along the axis of the cavity and that the field inside the cavity has a Gaussian profile, then the condition for start oscillations is given by [6]:

$$\eta = \frac{\pi}{16} \frac{\gamma_0}{\gamma_0 - 1} \left(\frac{E}{B_0} \right) \xi_0^2 \left(\frac{\beta_{e0}^2}{2} \xi_0^2 \frac{\Delta\omega}{\omega} - 1 \right) \exp - \frac{1}{2} \left(\xi_0 \frac{\Delta\omega}{\omega} \right)^2 \quad (12)$$

where $\xi_0 = (r_0 \omega / c) / \beta_{e0}$, with the maximum linear efficiency given by $\Delta\omega / \omega = 1 / \xi_0$.

The electric field modes in the resonator are derived by using the method of Fox and Li [16], which provides a good framework for solving problems with open resonators with non-trivial geometries such as mirror apertures. The method takes an initial electric field distribution and through a scalar diffraction integral and calculates the field distribution on the opposing mirror. This is iterated until a stable configuration is reached. The case of a central hole in one or both of the mirrors has been treated by various methods [17] [18] [19] [20]. The method is generalized for our experimental set-up.

For a resonator and azimuthal symmetry in the aperture geometry, it can be assumed that the fields are of the form:

$$u_n(r, \phi) = v_n(r, \phi) \exp(-in\phi) \quad (13)$$

where,

$$n = 0, 1, 2, 3 \dots$$

and ϕ is an azimuthal coordinate about the principal axis of the system. With these assumptions, the integral equations for the electric field profile are given by a one dimensional integral equation. The mirror-to-mirror field equation is then given below. The field v_1 at one mirror at a radius r_1 from the axis is integrated over that mirror surface A_1 with an appropriate symmetric kernel to give the field v_2 at the opposing surface A_2 as a function of r_2 . By the same process v_3 can be obtained.

$$\alpha_1 v_2(r_2) \sqrt{r_2} = \int_{A_1} K_n(r_2, r_1) v_1(r_1) \sqrt{r_1} dr_1 \quad (14)$$

$$\alpha_2 v_3(r_3) \sqrt{r_3} = \int_{A_2} K_n(r_3, r_2) v_2(r_2) \sqrt{r_2} dr_2 \quad (15)$$

where α_i is the complex loss coefficient, and K_n is a symmetric kernel that is given for mirrors of equal curvature by:

$$K_n(r_1, r_2) = \frac{j^{n+1}}{d} J_n \left(k \frac{r_1 r_2}{d} \right) \sqrt{r_1 r_2} \exp \left\{ -\frac{jk}{2d} (g r_1^2 + g r_2^2) \right\} \quad (16)$$

J_n refers to the nth-order Bessel function and $g = 1 - d/R$.

For confocal modes, $g = 0$, and the integral simplifies to the following:

$$v_2(r_2) = (2\pi/\lambda b) \int_{A_1} v_1(r_1) J_n(k r_1 r_2 / b) dr_1 \quad (17)$$

$$v_3(r_3) = (2\pi/\lambda b) \int_{A_2} v_2(r_2) J_n(k r_2 r_3 / b) dr_2 \quad (18)$$

where $k = 2\pi/\lambda$, b is the resonator spacing. These equations are then iterated until we have reached the condition for a resonant mode, when the field profile reproduces itself in a round trip through the cavity up to a constant,

$$v_3(r) = \alpha v_1(r) \quad (19)$$

If T is the power loss per round trip through the resonator, then we relate it to the constant α by:

$$T = (1 - \alpha^2) \quad (20)$$

For resonators in the microwave regime, the losses of the system can be characterized in terms of the Q of the system,

$$Q = -\omega \frac{E}{dE/dt}. \quad (21)$$

For a Fabry-Perot resonator the diffraction Q is given by:

$$Q_{diff} = \frac{2d\omega}{cT}. \quad (22)$$

where T is the total round trip loss. For the total Q , the term for ohmic losses must be included:

$$\frac{1}{Q} = \frac{1}{Q_{diff}} + \frac{1}{Q_{ohmic}} \quad (23)$$

The ohmic losses are given by [21],

$$Q_{ohmic} = \frac{d}{2} (\pi f \mu_0 \sigma)^{1/2} \quad (24)$$

For copper $\sigma = 3.6 \times 10^7$ siemens/m, which give for $f = 25$ GHz and $d = 17$ cm, then $Q_{ohmic} = 160,221$.

The small movable mirror arrangement can be studied by the overlap of modes created by the annular aperture (when the mirror is flush). High Q values are possible in this case as shown above. For the case of the smaller mirror extended in front of the larger mirror, the modes are studied as an asymmetric mirror pair. The interesting part of this configuration is that the longitudinal modes can be selected by the spacing of the larger and smaller mirrors. This arrangement has the advantage of shaping the profile along the axis, thus matching the annular profile of the electron beam for increased efficiency.

A computer simulation of the above model was performed on a Cray-2 system. The empty-resonator equations (15-19) are solved using a 32-point Gauss-Legendre scheme. The scheme is further enhanced by using an eigenvalue translation method which speeds the convergence to the mode solution with the largest eigenvalue. The final field solution is used to give the field at the center of the cavity

by the diffraction integral. The electric field profile is then approximated by a cubic scheme and is used to solve the equations of motion (4,5). A uniform phase distribution is assumed among a sample of 20 particles. The computer simulation allows the frequency ratio to be varied so as to optimize efficiency for a given electric field amplitude. This is the computational analog of adjusting the magnetic field or changing the resonator spacing in tuning the device for resonance. The electric field amplitude is varied until we satisfy the power balance in equation (8).

3.2 Discussion

As the beam profile changes, changes in the efficiency are expected. For the parameters $\alpha = 2.0$, $V=60\text{keV}$, a 6.27cm mirror radius, and an 18cm separation for the mirrors, the efficiency and start currents are studied. In Fig. 3 the efficiency is shown for different values of E/B for a resonator with no apertures so that the field profile is Gaussian. The maximum efficiency increases as E/B increases. In the case of the coupling mirror flush, this forms an annular aperture. The field profiles are predominately of the next higher symmetric mode order. In Fig. 4, for increasing values of E/B it can be seen that the maximum efficiency is higher. Maximum efficiencies occur at higher mismatches.

For small electric field strength the efficiency is linear to E^2 as stated before in the discussion of equation (12). As the electric field increases the efficiency saturates from its linear value at small fields. The start current is multiplied by the Q factor and is derived from the condition of equation. This product is higher in the profile in Fig. 4 than for the Gaussian profile. In the case of the extended mirror, the Q is lower so that the expected start current is higher. The range of the mismatch can be seen to be four percent. Since the efficiency of energy transfer saturates as the field strength increases, E^2/η_e is a decreasing function, and it can be seen by equation (11) that the current must increase from its initial value to satisfy the power balance. The current at steady state is twice the start current for a given Q .

As the mode changes the electron beam will encounter a different electric field distribution. Note that an increase in the transverse radial mode number requires a decrease in longitudinal mode number to maintain the same frequency. For a beam of finite cross-section and annular geometry, individual

electrons experience longitudinal variations in the electric field. The dependence of the efficiency on the electric field implies that a uniform distribution of the fields is necessary for high efficiency. This can be seen in a superposition of the first two modes (predominately TEM_{20}) as shown in Fig. 5 along with the electron beam profile. Since the electric field saturates in efficiency, it may not be necessary to be at the peak electric field points for optimum efficiency. The coupling aperture superimposes the two fields to maximize the efficiency of energy transfer. Simulations show that with an annular electron beam profile that the efficiency can be improved in this manner.

4 Experimental Results

4.1 Microwave Bench Results

A schematic of the microwave bench test is shown in Fig. 6. A YIG oscillator provides microwave radiation at 26.5-40 GHz at a power level of 10mW. The oscillator is modulated to sweep across a bandwidth of 31MHz about the operating frequency. The signal is transferred to the resonator in the TE_{10} mode by a standard WR28 waveguide. Along the waveguide is a cylindrical resonant stub that serves as a frequency calibration. Additional resonant stubs are used to impedance match the waveguide radiation to the resonator. The waveguide is connected to a rectangular recess of the passive mirror. A 1mm hole is drilled through the center of the resonator to allow a small fraction of the microwaves through from either direction. The size of the hole is chosen so that the signal is easily detectable while the perturbation to the resonator is negligible. The passive mirror is positioned on an optical mount that allows for a greater than 5 degree tilt from the mirror plane. The coupling mirror is mounted on a dual drive assembly that allows for changing the spacing between the large mirrors and the spacing of the smaller coupling mirror relative to the larger coupling mirror. The output is coupled through a cylindrical waveguide. The waveguide end is slowly transitioned to a WR-28 waveguide with a crystal diode detector as a termination. This transition is removable for the examination of the output radiation profile. The amplitude of the diode signal is measured as a function of frequency. For a Lorentzian line shape the bandwidth around the resonance at f gives the Q of the cavity by way of $Q = \Delta f/f$. [22]

For a given frequency and for d/R near 1, the mode spectrum has a constant spacing between different longitudinal modes. This spacing is then used to find the radial mode number. With large resonators, there exists more than one transverse mode with small losses if the coupling aperture is not present. With the coupling aperture, a number of the lower order modes with larger field profiles at the aperture will have strong coupling and a lower Q . By conveniently choosing the mirror sizes, one can choose a specific mode that has both a high Q and losses predominately at the aperture.

With the smaller movable mirror extended, points of relatively high amplitude signals are seen at a distance close to half a wavelength. At a frequency of 30 GHz, the movable mirror is extended a distance to a distance of .55cm from the larger mirror. In Fig. 7, the signal on the crystal diode is shown to be an increasing function of the large mirror separation. The $Q \sim 8000$ resonance corresponds to a Gaussian mode between the secondary mirror and the passive mirror. The other resonance appears to be a collection of higher order modes closely spaced in a frequency interval that have fields near the outer edges of the larger coupling mirror.

As the smaller mirror is moved closer toward the larger coupling mirror, two resonant modes approach each other in frequency space. At the point of being flush, the two modes combine; they correspond to a linear combination of the fundamental and the next cylindrically symmetric mode TEM_{10} , as tested by passing an absorbing substance through the resonator. Since the drop is only a local perturbation of the electromagnetic mode profile the proportional decrease in output signal provides an indication of the electric field strength at various points along its path. The combination of a thick shampoo along the guiding path of a long taut strand of hair made for a convenient trace of the mode shape. This test only shows larger perturbations from Gaussian modes as smaller variations of higher order radial modes are not easily distinguishable. Other modes also appear when the spacing of the combined arrangement is changed. The Q is shown as a function of mirror spacing for these modes. The Q in the nonconfocal spacing does not change. The fact that the Q does not correlate with amplitude of signal shows that the energy is lost by diffraction about the larger mirror. A small decrease is observed in amplitude as the separation increases. This is summarized in Fig. 8.

The output profile is studied by placing a microwave horn in the far-field. The choice of distance is determined by the signal to noise ratio. A convenient distance is chosen where near field effects are negligible. The half amplitude points from the output axis is recorded. The finite size of the microwave horn inhibits an accurate assessment of the actual beam profile. However the angular spread is largely determined by the output wave mode. The angular spread is measured to be approximately 10 degrees in the horizontal plane, which corresponds to a predominately TE_{10} circular waveguide mode.[23]

4.2 High Power Results

A sample oscilloscope trace from the photon drag detector is shown in Fig. 9(a) along with the signal from the crystal diode. The signal represents a 40 μ s pulse at a peak power level of 67kW at a frequency of 25GHz. The input electron beam parameters are 60.8kV and 2.5A, giving an overall efficiency of 38%. This is slightly higher than expected from the single mode calculation, although efficiencies of this magnitude appear to be possible as shown in Fig. 3 and 4. The crystal diode signal is saturated at this power level and does not give additional information. In Fig. 9(b), the current pulse is displayed for the same parameters. The conversion of the voltage response of the photon drag detector may not be an accurate assessment of the power output due to radial dependence of both the output radiation and the detector currents.

A static water calorimeter of a flat disk geometry is used to verify the power output. The high efficiency operating mode is sensitive to the magnetic field and beam parameters. The calorimeter can not be used independently to verify the power output; its reaction is slow compared to the fluctuation of the beam current and voltage due to the transient heating effects and other causes that detune the device from resonance. It is possible to reflect the signal off of the planer surface of the calorimeter onto the photon drag detector, allowing the device to be tuned to resonance by examining the photon drag signal. The water calorimeter does not couple the microwave energy well and indicates a lower than actual energy. Even at conservative estimates of performance, the calorimeter set a lower bound for the efficiency of operation to be 10%, when various factors such as the duty cycle of the pulse,

reflectivity, and thermal losses are considered.

The lowest current levels at which oscillations begin to occur appear to be approximately 1-1.5 A. This is slightly higher than that predicted by the small signal calculations of less than 1A for the Q calculated by the bench test. Although operation can occur at higher beam currents, increases of current do not result in higher power outputs. This limitation is possibly due to lower beam quality at higher beam currents or parasitic modes with lower power outputs and lower Q as observed in the microwave bench test.

An interesting feature of this trace is the long rise and decay times of the pulse which are usually indicative of a resonator of high Q. The long rise and decay times occur regardless of the pulse length. If the exponential decay time is related to the Q through its standard definition from equation (21), the Q is found to be on the order of 10^6 . This is an order of magnitude higher than the Q measured from our bench testing and from our calculated results, which were on the order of 10^4 . Since the ohmic Q, approximately 160,000, is the upper limit for the resonator Q, the rise time must then be attributed to other causes, perhaps to electron beam effects.

For a given current of 2.5A and voltage of 64kV, the magnetic field can be changed. The location of a higher efficiency mode is shown in Fig. 10 for different large mirror spacings. This corresponds to changes in the longitudinal mode spacing. The bandwidth of the instability is on the order of this mode spacing such that the location of resonance is not uniform. Thermal effects on the cathode make it difficult to maintain the current and voltage fixed. The increase in mirror separation shows a general effect of lowering the power output, although a resonant point can be seen for the 14.45cm spacing deviates from this. Furthermore the 5V signal observed at the same parameters taken at a different run.

In Fig. 11, the shift in magnetic field needed to maintain resonance at the specific mode is shown as a function of increasing voltage. This roughly correlates to the change in γ due to the increased voltage, and therefore an increase in B is necessary to maintain a given ω . In general, the frequency mismatch between the resonator mode and the gyrofrequency is not a constant. The spacing between

modes corresponds to the fundamental beat frequency as expected. A change in the mirror spacing brings only a small change in power output. The bandwidth of the resonance is given by Fig. 12 to be 5%, large relative to the frequency shifts due to this change.

5 Conclusion

The observation of a high efficiency of operation merits additional study. A better correlation between the photon drag and calorimeter diagnostic measurements is necessary. A measurement of output beam energy and profile will also improve an understanding of experimental results, especially in the lack of increase of output power with increased currents. Theoretical calculations allow for a reasonable assessment of the modes in an open resonator with output coupling mirror. The effects of the modes on the efficiency of coupling to an electron beam have been studied and show that a high efficiency is possible. Studies are necessary to determine possible mechanisms which diminish output efficiency at higher power inputs, such as simulations of multimode and electron beam effects.

Fig. 1 A Cassegrain coupling scheme is shown in (a). In (b), a scheme using a movable secondary mirror.

Fig. 2 Experimental schematic using the movable mirror coupling schemes.

Fig. 3 Electronic efficiency vs E_{peak}^2 for $dw = 1 - 1/\gamma r$ for the electric field profiles shown.

Fig. 4 Electronic efficiency vs E_{prak}^2 for $dw = 1 - 1/\gamma$ for the electric field profiles shown.

Fig. 5 Longitudinal profile of a superposition of two modes.

Fig. 6 Microwave bench set-up.

Fig. 7 The amplitude of the signal is shown for the smaller mirror extended. The smaller mirror is extended .217 inches from being flush from the larger mirror. The frequency is at 30 GHz.

Fig. 8 The amplitude of the signal is shown for the smaller mirror flush. The frequency is at 30 GHz.

Fig. 9 Oscilloscope trace for (a) photon drag and current pulse. Experimental parameters are $I=2.5\text{A}$, $V=60\text{kV}$, $B=9.5\text{kG}$, $f=25\text{GHz}$.

Photon Drag (in Volts*50)

15.11cm 14.45cm 13.25cm

○ ▽ □

Fig. 10 Magnetic field vs. mirror separation. The values for the monitor of the current shunt on the magnetic field is given for high Q resonances at different passive mirror spacing.

B-Current (39=1Tesla)

Fig. 11 Magnetic field vs. beam voltage. The change in the magnetic field to maintain resonance as a function of changing beam voltage is plotted.

B-Current (39=1Tesla)

Fig. 12 The photon signal vs. magnetic field for three cavity separation. The parameters are for $I=2.5A$, $V=64kV$.

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