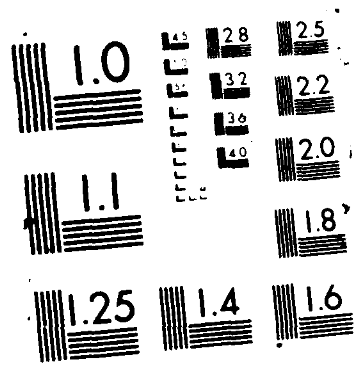
AD-A186 066 HIGH REPETITION RATE ELECTRON BEAM RF-ACCELERATION AND SUB-MILLIMETER WAV..(U) CALIFORNIA UNIV LOS ANGELES N C LUHMANN ET AL. 14 AUG 87 N00014-84-K-0569

1/1

UNCLASSIFIED

F/G 9/3

NL


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0

AD-A186 066

ANNUAL PROGRESS REPORT

1. ONR Proposal Number: P-5610-N-84

2. Period Covered by Report: 15 August, 1986 - 14 August, 1987

3. Title of Proposal: High Repetition Rate Electron Beam RF-Acceleration and Sub-Millimeter Wave Generation via a Free Electron Laser

4. Contract or Grant Number: N00014-84-K-0569

5. Name of Institution: University of California, Los Angeles

6. Author(s) of Report: N.C. Luhmann, Jr. and D.B. McDermott

7. List of Manuscripts Submitted or Published under ONR Sponsorship During this Period, Including Journal References:

(a) D.B. McDermott, D.S. Furuno, N.C. Luhmann, Jr., W.J. Nunan, Haibo Cao, "Compact, High Power Millimeter Wave Sources," Proc. of Sixth Int. Conf. High Power Particle Beams, Osaka, Japan (1986).

(b) D.B. McDermott, W.J. Nunan and N.C. Luhmann, Jr., "A Prebunched 94 GHz Free Electron Laser," Proc. of the Eleventh IEEE Int. Conf. IR and mm-Waves, Pisa, Italy (1986).

(c) W.J. Nunan, D.B. McDermott and N.C. Luhmann, Jr., "A High Duty Cycle, Compact 94 GHz FEL," Bull. APS 31, 1482 (1986).

(d) D.B. McDermott, K.Z. Cheng and N.C. Luhmann, Jr., "A Prebunched FEL," 1987 IEEE Int. Conf. on Plasma Science, Arlington, Virginia (1987).

(e) D.B. McDermott, K.C. Leou and N.C. Luhmann, Jr., "A Prebunched 94 GHz Free Electron Laser," Fourth Int. Symposium on Gyrotron and FEL, Chengdu, China (1987), to be published in special issue of Inter. J. Electronics, (1987).

(f) A.T. Lin, D.B. McDermott, N.C. Luhmann, Jr., D.S. Furuno, T.H. Kho, H.B. Cao, C.S. Kou, K.Z Cheng, "Fast Wave Device Research at UCLA," High-Power Millimeter Wave Fast Wave Devices Workshop, Naval Research Lab, Washington, D.C. (1987).

(g) K.C. Leou, D.B. McDermott, N.C. Luhmann, Jr., "High Repetition Rate RF-Acceleration for a Millimeter Wave FEL," submitted to Twenty-Ninth APS Plasma Annual Meeting (November, 1987).

(h) D.B. McDermott, K.C. Leou and N.C. Luhmann, Jr., "A Prebunched Free Electron Laser," to be published in Proc. of the Twelfth IEEE Int. Conf. IR and MM-Waves (1987).

(i) Q.S. Wang, T.H. Kho, A.T. Lin, D.B. McDermott and N.C. Luhmann, Jr., "Enhancement of Traveling Wave Gain and Efficiency with a Phase Filter," to be published in Proc. of the Twelfth IEEE Int. Conf. IR and MM-Waves (1987).

(j) Q.S. Wang, T.H. Kho, A.T. Lin, D.B. McDermott and N.C. Luhmann, Jr., "Enhancement of Traveling Wave Gain and Efficiency with a Phase Filter," to be published in Tech. Digest IEDM (1987).

8. Scientific Personnel Supported by This Project and Degrees Awarded During This Reporting Period:

Prof. N.C. Luhmann, Jr.

Dr. D.B. McDermott

W.J. Nunan (Ph.D. Student)

K.Z Cheng (Ph.D. Student)

K. C Leou (Ph.D. Student)

PROGRESS

I. THEORY

A. Prebunched FEL

We have previously reported that no deleterious effects are expected to occur due to the electron beam being in the form of a series of micropulses other than the gain being determined by the average macropulse beam current. In fact, short electron pulses can even enhance FEL gain. First-order effects become dominant as the spatial extent of the electron pulse becomes much shorter than the rf wavelength. Here, all electrons are either accelerated or decelerated in the beat wave of the undulator and rf. This is in contrast to the usual second-order FEL interaction where gain occurs due to a slight dominance of deceleration over acceleration as the energy transfer is integrated over the initially random particle phase. For this effect to be exploited usefully, the FEL rf driver source must be locked to a harmonic of the accelerator's frequency in the case of an amplifier, and for an oscillator the cavity must be tuned to this frequency.

Colson[1] gives the energy loss (or gain) of an electron propagating through an undulator in the presence of a circularly polarized electromagnetic wave of frequency, ω and amplitude, E.

$$\frac{\Delta\gamma}{\gamma} = \frac{2}{(1+K^2)^{3/2}} \left[\frac{\Omega}{\omega}\right] \left[\frac{eE}{m_0 c}\right] \Xi \qquad (1)$$

where

$$\Xi = \frac{\cos(\Delta\omega\tau + \varepsilon_0) - \cos\varepsilon_0}{\Delta\omega}, \qquad (2)$$

$\Delta\omega$ is the frequency difference of ω from the synchronous frequency, ε_0 is the phase position of the electron in the beat wave of the rf wave with the undulator with period, λ, $\Omega = eB_\perp / m_0 c$ with $B_\perp$ representing the strength of the helical magnetic field and $K = (\lambda\Omega)/(2\pi\beta_\parallel c)$.

Maximum energy loss occurs for electrons bunched at the phase $\varepsilon_0 = \pi/2$. For this value $\Xi = -\sin(\Delta\omega\tau)/(\Delta\omega\tau)$, which is proportional to the linewidth of the spontaneous emission. This interaction will therefore be much less sensitive to a spread of the beam's velocity. For synchronism of the electrons with the beat wave ($\Delta\omega = 0$), $\Xi = -\tau$. The power transferred to the wave is

$$\Delta P = -(m_0 c^2/e) I \Delta\gamma \qquad (3)$$

where I represents the electron beam current averaged over the macropulse.

First we will look at an amplifier. The differential equation for the amplifier's output power is found by inserting Eq. 1 into Eq. 3.

$$\delta P = X P^{1/2} \delta z \qquad (4)$$

where

$$X = \frac{-2I\gamma}{\beta_z[1+K^2]^{3/2}} \left(\frac{\Omega}{\omega}\right) \left(\frac{8\pi}{Ac}\right)^{1/2} \qquad (5)$$

In the above, β_z is the electron's axial velocity normalized to the speed of light and A is the effective cross-sectional area of the electromagnetic wave. After integrating over the entire length, L, of the interaction and ignoring coupling losses, we find that gain is given by

$$\frac{P_{out}}{P_{in}} = \left[1+\frac{\gamma I}{\beta_z(1+K^2)^{3/2}}\left[\frac{\Omega}{\omega}\right]\left[\frac{8\pi c}{P_{in}A}\right]^{1/2} L\right]^2 \tag{6}$$

where P_{in} and P_{out} are the input and output rf power, respectively. Unlike stimulated emission, in which small signal gain is independent of the wave's amplitude, the gain from this interaction is approximately inversely proportional to the input power. For the parameters listed previously for the planned conventional FEL experiment, the predicted gain is 64 dB for an input power of 40 mW, whereas the conventional non-prebunched FEL interaction is expected to yield a gain of approximately 10 dB after accounting for the finite velocity spread of the electron beam. These results were published in the Proceedings of the Eleventh Int. Conf. on IR and Millimeter Waves (1986).

Since the output from this interaction can easily grow to saturation from noise it is more relevant to study this process in an oscillator configuration. In a steady-state oscillator the power emitted by the electrons will equal the sum of the Ohmic and diffractive losses. The dissipated power is simply given by

$$P = \frac{\omega U}{Q_L} \tag{7}$$

where U is the cavity's stored energy and Q_L is its loaded quality factor.

In Colson's analysis a plane wave was assumed. To more accurately model the experiment we replace the plane wave by a TE_{11P} mode of the cylindrical cavity. We then have

$$U = La^2E^2(1-q_{11}^{-2})J_1^2(q_{11}) \tag{8}$$

where a represents the cavity's radius, $J_1(y)$ the first order Bessel function, and q_{11} the first zero of dJ(y)/dy. Using Eqs. 1 and 6, Eq. 5 can be rewritten

$$\frac{-2\gamma I}{(1+K^2)}\left(\frac{\Omega}{\omega}\right)\left(\frac{L}{\beta_z}\right) E = \frac{\omega}{Q}\, La^2E^2(1-q_{11}^{-2})J_1^2(q_{11}) \tag{9}$$

The wave's electric field reaches the level

$$E = \frac{2Q\gamma I\Omega}{\omega^2a^2(1+K^2)\beta_z(1-q_{11}^2)J_1^2(q_{11})} \tag{10}$$

This corresponds to a conversion power in mks units of

$$P = \frac{4\times10^{-5}c^2\gamma^2QI^2}{(1+K^2)^2\beta_z^2\omega}\left(\frac{\Omega}{\omega}\right)^2\frac{L}{a^2}\left[\frac{1}{(1-q_{11}^2)}\,\frac{1}{J_1^2(q_{11})}\right] \tag{11}$$

For the experimental parameters of γ=2, I = 1A, $B_\perp$ = 1 kG, l = 3cm, and L = 30cm the output power from a critically coupled 28 GHz cavity with a Q of 100 is predicted to be 10 kW. Since this is an appreciable fraction of the 500 kW beam power, we must substantiate this claim with at least a qualitative saturation analysis. The efficiency is determined by the dependence of the resonance condition on the energy, which for an interaction in free space can be written

$$\omega = \frac{\omega_o}{1-\beta_z} \tag{12}$$

where $\omega_o = k_oc\beta_z$ with $k_o = 2\pi/l$ representing the wavevector of the undulator. As the electrons lose energy they fall out of resonance. The dynamic phase shift of an electron relative to the beam wave is

$$\Delta\phi = \frac{(1+\beta_z)}{\beta_z}\,\frac{\Delta\gamma}{\gamma}\,\omega\tau \tag{13}$$

where τ is the duration of the interaction. Since the electrons should slip back in phase by no more than π the maximum conversion efficiency is

$$\eta = \left(\frac{\gamma}{\gamma-1}\right)\left(\frac{\beta_z}{1+\beta_z}\right)\frac{\pi c}{\omega L} \tag{14}$$

which yields a predicted efficiency of 2% for the experimental parameters listed above. We find therefore that the previously stated output power of 10 kW is justified. The efficiency can be increased considerably by tapering either the amplitude of the undulator as in the FEL at the Lawrence Livermore Laboratory or its period. For all electrons to lose energy in this pre-bunched FEL-klystron they must be properly phased with respect to the beat wave. This can only be satisfied if the micropulse length of the electron beam is much less than the rf wavelength. We have seen in simulations that the beam which will interact with the wave (i.e., within a 1% energy spread) has been compressed by the accelerator into 1% of its rf cycle. Therefore, the maximum harmonic of the accelerator which can be produced by this beam is 50. Though our beam will not interact constructively at 94 GHz via this stronger, lower order FEL, it can emit at frequencies as high as 60 GHz. Since the limit of this interaction scales with the frequency of the accelerator, higher frequency output can be trivially attained with a higher frequency driver. For example, a 3 GHz accelerator can give rise to FEL-klystron output at frequencies up to 150 GHz.

Though an FEL is usually designed to emit at high frequency let us investigate its lower frequency properties. The lower frequency limit of any FEL is influenced by the cutoff frequency of the waveguide, ω_c. For frequencies near the cutoff, the waveguide dispersion appreciably affects the resonance condition. Instead of Eq. 12, the true resonance condition is

$$\omega = \frac{\omega_0}{1 - \left[1 - \left(\frac{\omega_c}{\omega}\right)^2\right]^{1/2}\beta_z} \tag{15}$$

For $\omega_c > ck_0$, as in our FEL and shown in Fig. 1a, the lowest frequency achievable is

$$\omega = \omega_c\,\frac{[1 + (\omega_c/ck_0)^2]^{1/2}}{2} \equiv \omega_{min} \tag{16}$$

and this occurs for $\beta_z = 1$! Also of interest, for this case a backward wave cannot be excited. Both intersections of the beam mode with the electromagnetic wave occur as forward waves. An absolute instability is therefore not expected. However, if $ck_0 > \omega_c$, a backward wave <u>can</u> be excited as shown in Fig. 1b.

B. Harmonic Klystron (Prebuncher Diagnostic)

We have reported in earlier papers that a buncher cavity between the electron gun and accelerator can improve the quality of the accelerated beam. The buncher has two adjustable parameters, the input power and its phase with respect to the accelerator. The input power determines the bunching parameter, which is a measure of the extent of bunching. The buncher cavity's phase controls the phase at which the electron pulses enter the accelerator and thus their

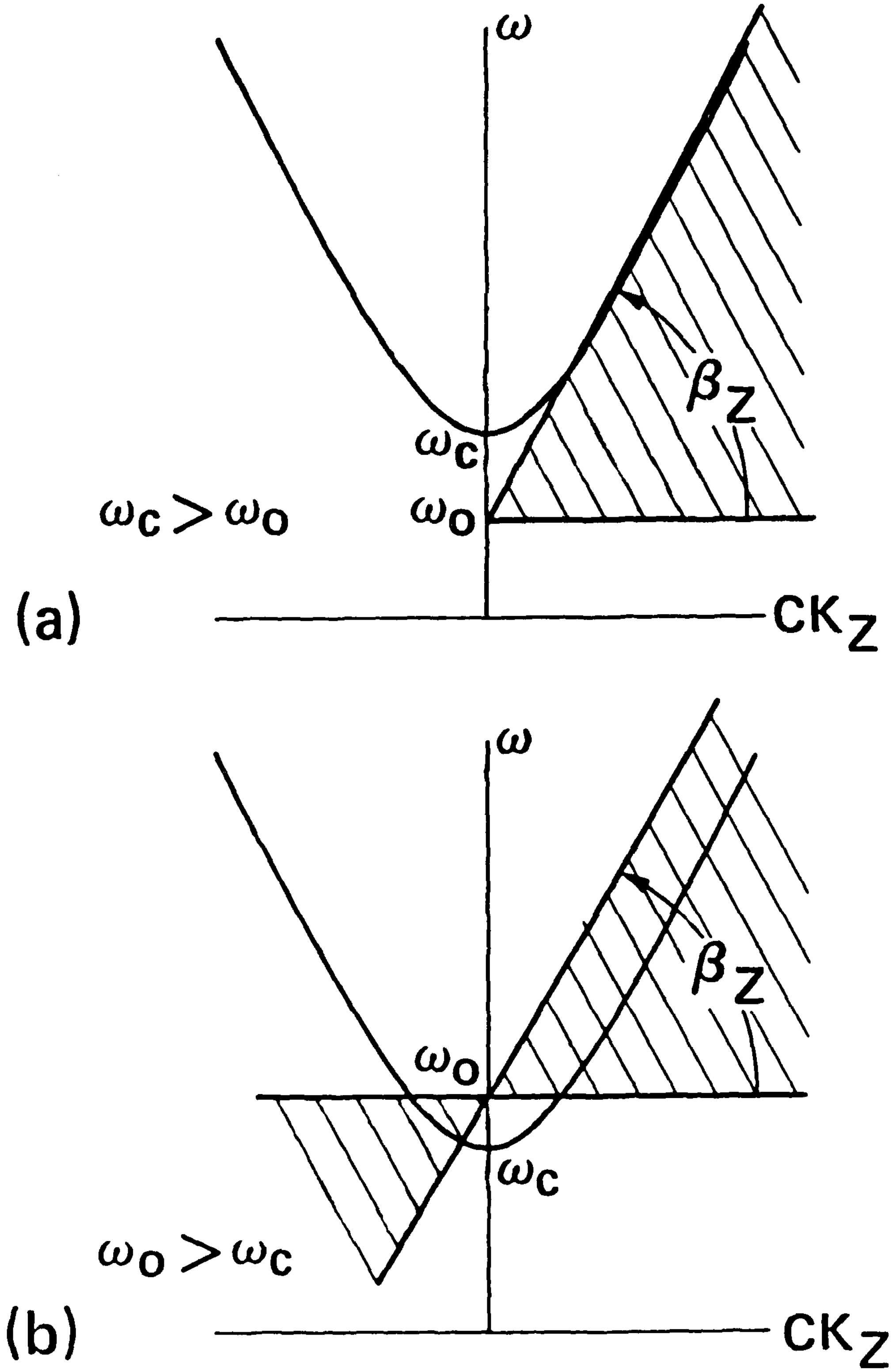


Figure 1 Accessible beam-wave intersections in FEL with (a) $\omega_c > \omega_o$ and (b) $\omega_o > \omega_c$.

final energy. The final beam would be most monoenergetic if all electrons entered the cavity simultaneously, i.e. the input beam to the accelerator should resemble a periodic delta function. A diagnostic was devised, constructed and tested to measure the beam's resemblance to a delta function and thereby allow the operator to judge the optimum microwave power into the buncher. A catcher cavity whose TM_{010} mode is tuned to a harmonic of the accelerator will be excited by a sharp periodic beam pulse because of its rich Fourier content. The optimum input power into the buncher is thereby found by maximizing the signal from the harmonic catcher cavity.

For this diagnostic to not perturb the beam significantly the cavity should extract only a very small amount of energy from the beam. We will now derive an expression for the energy lost by the electrons as they transit this cavity. The power lost by the beam to the wave is

$$P_b = \hat{V}\hat{I} = \beta l E_o \hat{I} \tag{17}$$

where l is the cavity's length, E_o is the amplitude of the wave's electric field, β is the beam-coupling coefficient (=1 for an infinitesimally short cavity) and $\hat{I}$ is the component of the beam current at the cavity's resonant frequency, f. The power lost by the cavity is

$$P_c = \frac{2\pi f_c}{Q} U \tag{18}$$

where Q is the cavity's quality factor and U is the wave's energy. In cgs units for the TM_{010} mode

$$U = (0.3338) l a^2 E_o^2 \tag{19}$$

where a is the cavity's radius.

At equilibrium the power gained by the cavity wave is balanced by power loss. Setting Eqs. 17 and 18 equal leads to

$$E_o = \frac{\beta Q_L \hat{I}}{(0.21)a^2 f} \tag{20}$$

This expression can be used to find either the power emitted by the cavity or the beam's energy loss. The power emitted by the cavity is

$$P_{rf} = [\frac{\beta_c}{1+\beta_c}]P_c = [\frac{\beta_c}{1+\beta_c}]\frac{\beta^2 Q_L \hat{I}^2}{(0.21)a^2 f} \tag{21}$$

where β_c represents the cavity's rf coupling coefficient (=1 for critical coupling). The relative voltage drop in the beam due to the bunching diagnostic is

$$\frac{\Delta V}{V_o} = \frac{\beta^2 Q_L \hat{I}}{(0.21) I_o V_o f a^2} \tag{22}$$

where V_o is the initial voltage of the beam.

The rf current $\hat{I}$ must now be calculated. Though the accelerator itself bunches the beam, to first order only the buncher cavity produces bunching. In this model it is assumed that the accelerator merely transforms the beam through space with an energy boost. The buncher cavity of a klystron produces a current at the nth harmonic of the driver frequency equal to

$$\hat{I} = 2 I_o J_n(n\chi) \tag{23}$$

where I_o is the average macropulse current and χ is the bunching parameter which for a given drift length is controlled by adjusting the power into the buncher. For maximum nth harmonic current

$$n\chi = q_{n1} \tag{24}$$

where q_{n1} is the first zero of $J_n'(y)$. If we use this expression and the dependence of the harmonic catcher frequency on radius

$$f = \frac{0.38c}{a} \tag{25}$$

then the voltage drop and output power can be written

$$\frac{\Delta V}{V_o} = \frac{50 J_n(q_{n1}) \beta^2 Q_L I_o}{c V_o} \left(\frac{l}{a}\right) \tag{26}$$

and

$$P_{rf} = \left[\frac{\beta_c}{1+\beta_c}\right] \frac{50[J_n(q_{n1})]^2 \beta^2 Q I_o^2}{c} \left(\frac{l}{a}\right) \tag{27}$$

For a critically coupled cavity with $l/a = 0.2$ and a loaded Q of 100, the power emitted at the ninth harmonic by a bunched 1A beam with $\chi \simeq 1$ will be 600 W and the relative voltage drop will be 0.2%.

C. Enhancement of Travelling Wave Gain

We have begun to investigate a scheme to enhance travelling wave interactions (TWIs). This technique has been introduced by A.T. Lin[2] to enhance the efficiency of a Cyclotron Autoresonant Maser (CARM), but we recognize its applicability to all TWIs including the FEL. The approach will now be described. In any TWI half of the beam gains energy while the other half loses energy. For synchronism of the beam with the wave the two terms exactly cancel and there is no net power transfer. Energy loss dominates gain when the beam is properly mistuned from synchronism. ~~Lin's~~ enhancement scheme for the CARM, ~~which we~~ recognize as appropriate for any TWI, is to effectively suppress the electrons which are phased to gain energy by using the gyro-resonant properties of a FEL wiggler. This enhancement wiggler is distinct from the FEL wiggler. For any uniform magnetic field there is an axial velocity at which an electron is gyro-resonant with the wiggler period, which is

$$v_z = \frac{l\Omega_{co}}{2\pi\gamma} \tag{28}$$

where $\Omega_{co} = eB/m_o c$ is the rest mass cyclotron frequency. If Eq. 28 is satisfied the periodic $v_z \times B_\perp$ force drives the particles at their natural frequency, the cyclotron frequency, and their transverse velocity grows linearly, given by

$$v_\perp = \left(\frac{eB_\perp}{\gamma mc}\right) z \tag{29}$$

The value of $\alpha = v_\perp / v_z$ at the exit of a ten period undulator as a function of the wiggler field amplitude for a 75 keV electron is shown in Fig. 2 for several values of initial resonance ratio, R, where R is defined as

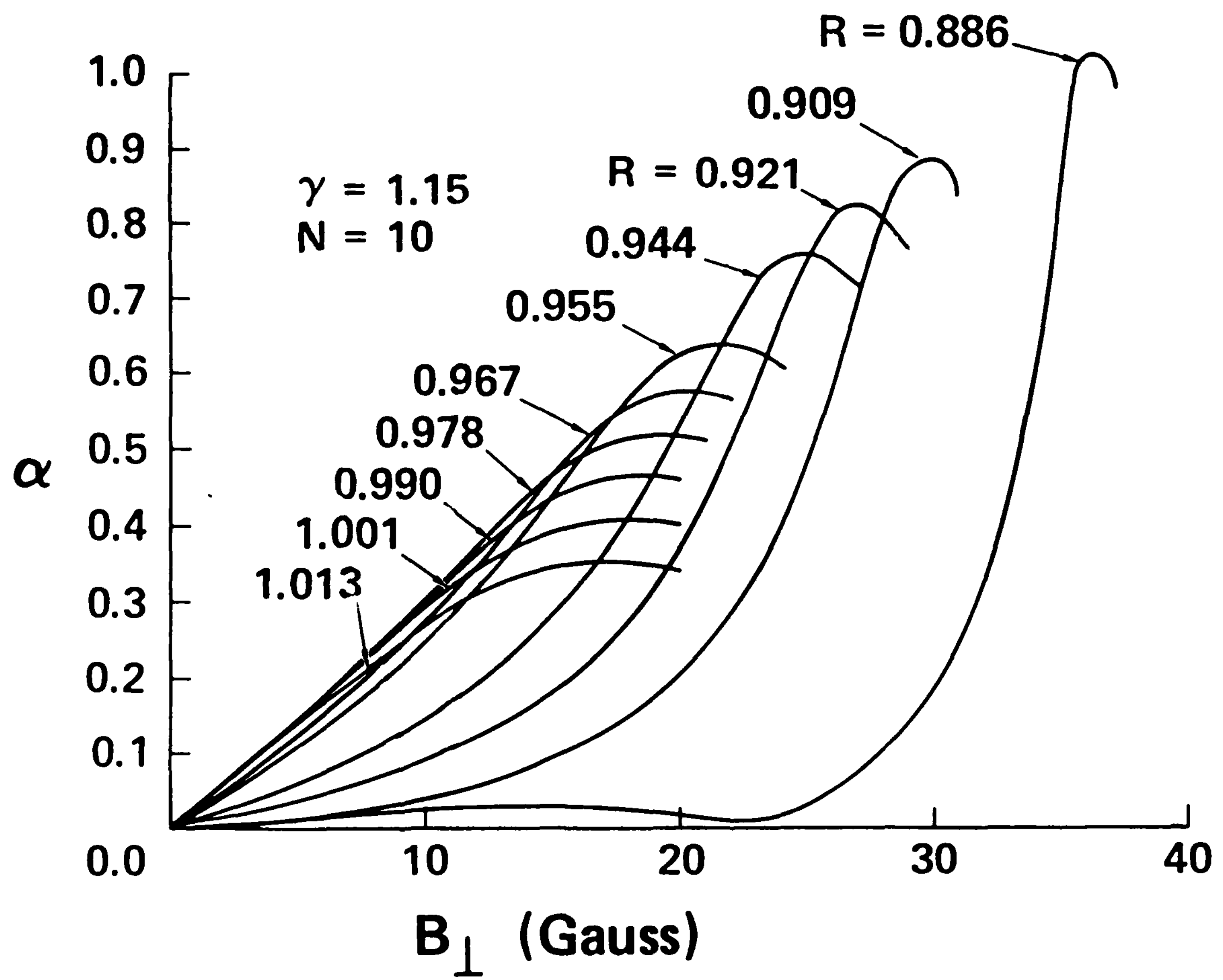


Figure 2 Dependence of final α ($= v_{\perp}/v_z$) at exit of ten period undulator on intensity of wiggler's transverse magnetic field for several values.

$$R \equiv \frac{l\Omega_{co}}{2\pi\gamma v_z} \qquad (30)$$

Since a magnetic field cannot alter the energy of a particle, as the transverse energy increases the longitudinal velocity must decrease.

A wiggler could best be used to enhance a TWI by choosing its period so that the gyro-resonant velocity (Eq. 28) is slightly greater than the TWI resonant velocity. In this way the electrons that gain energy from the wave become more resonant with the wiggler, thereby falling out of resonance with the wave, and thus not taking as much energy from the wave as they would have. Lin has found that the efficiency of a CARM can be increased by as much as 200% with a wiggler used in this fashion. It should be stressed that for an FEL this gyro-resonant wiggler would be distinct from the main wiggler. Whereas the main wiggler produces a field on the order of 1 kG, the field from the gyro-resonant wiggler is only about 10 G.

II. EXPERIMENT

A. Enhancement of Travelling Wave Gain

We have begun to construct an experiment to test this enhancement scheme on one of our existing commercial TWT tubes, the 300 kW L-band QKW1518SG, which is solenoid-focused as required. The 50 keV electrons would be gyro-resonant with a wiggler with a period of 9 cm for the suggested magnetic field of 500 G. For the electrons which are phased to lose energy to be relatively unaffected, the period should be approximately 10 cm. The tube's 110 cm helix would then be spanned by an eleven turn wiggler. A current of 1 kA through a 10 turn wiggler with a radius of 11.5 cm (to slide over the tube with an outer diameter of 21 cm) would produce the desired transverse field of 10 G on axis. We will look for an increase in power level beyond the tube's present capability of 300 kW as the wiggler field is increased. It should be emphasized that this tube is available in our lab along with the working modulator. The major remaining component to be fabricated is a large diameter wiggler. The requisite 500 G solenoid to be slid over the wiggler has been wound. A 100V, 50A power supply is being reconditioned. This important technique can be checked quickly and cheaply. The advantages of this idea are enormous. Lin has shown in particle simulations that the CARM's efficiency can be improved by a factor of three and the electron beam velocity spread requirements can be relaxed by nearly a factor of four.

B. Solenoid

A large bore, air-core, solenoid water-cooled system has been assembled to constrain the electron beam and guide it from the electron gun, through the accelerator and then through the free electron laser tube. It is shown in Fig. 3. Its field profile is shown in Fig. 4 together with the placement of the major experimental components. The electron beam emerging from the cathode has a diameter of 6.35 mm. Due to an eight-fold compression of magnetic field its diameter is 2.3 mm as it propagates through the FEL interaction tube. The reason for the strong magnetic field peak near the center of the solenoid is to further compress the beam as it passes through a hole in the mirror for the reflection amplifier experiment. The magnetic field in the FEL interaction region can be raised as high as 1.6 kG on a steady state basis.

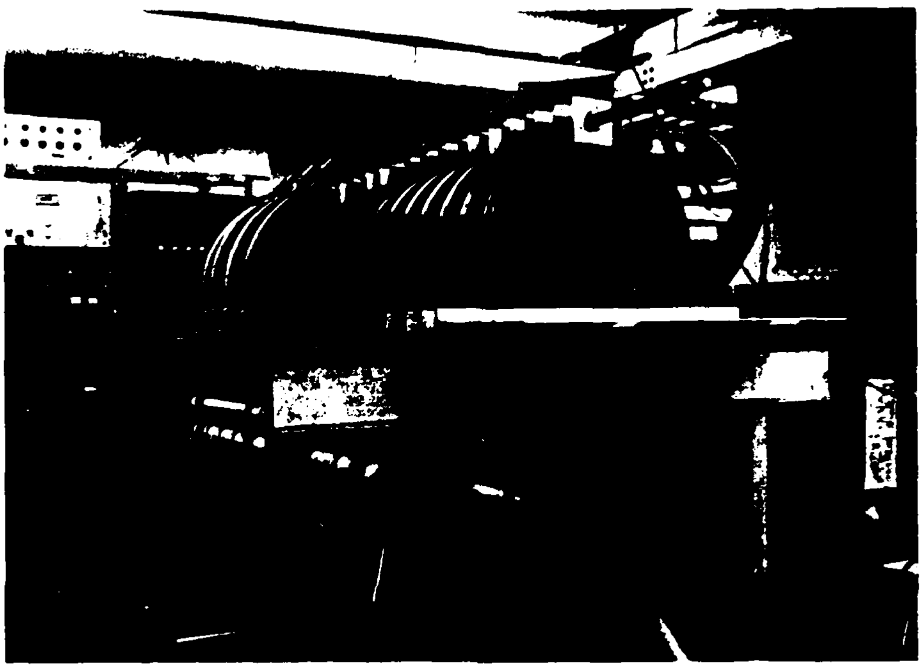


Figure 3 Photograph of solenoid with magnetron and electron gun modulator in background.

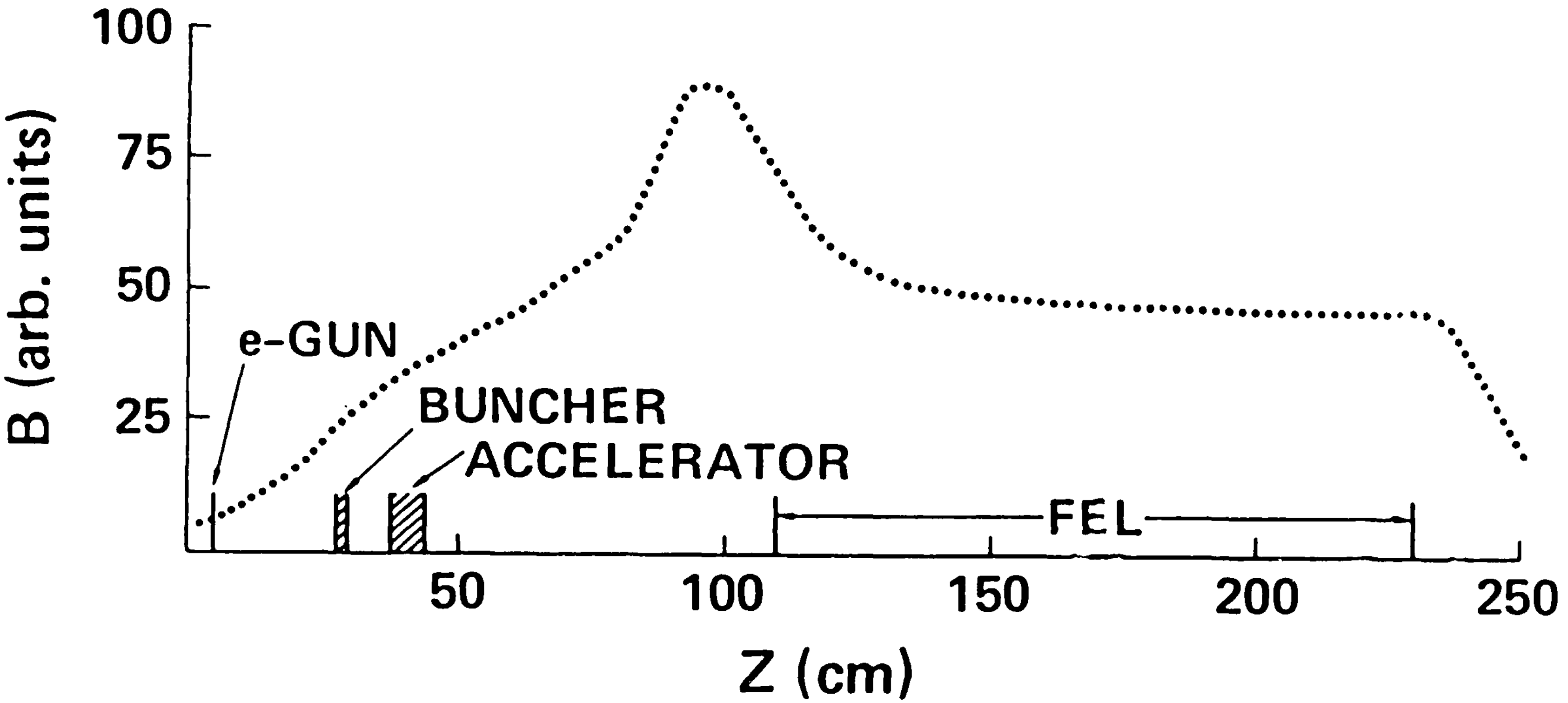


Figure 4 Spatial dependence of solenoid's magnetic field.

The initial acceleration experiments were performed in yet another magnet configuration. To begin experiments while the final solenoid was being assembled we used a single pancake magnet as shown in Fig. 5. The accelerator cavity was placed at the field maximum while the electron gun and current collector were in the fringing fields on opposite sides of the solenoid.

B. Accelerator

Figures 6-8 show Smith chart measurements of the TM_{010} mode of the accelerator cavity as produced by a Hewlett-Packard 8408S Automatic Network Analyzer. From Fig. 6 the unloaded quality factor is seen to be 2950. The external Q from Fig. 7 is 920 for a coupling coefficient of 3.2 (overcoupled). These two quantities imply the loaded Q, Q_L, should be 700. This is in close agreement with the direct measurement of Q_L shown in Fig. 8, which yields the value of 610. If it is desired to increase the unloaded Q, then the stainless steel face of the cavity which is welded to the waveguide should be electroplated with copper. If it is desired to decrease the coupling coefficient towards critical coupling, then the coupling aperture can be reduced with an available plate.

The magnetron's output has been directed into the accelerator. We were until recently limited by arcing in the cavity to a power level of only 1 MW. The arcing occurred due to poor current continuity between the two sections of the cavity. We have taken steps to ensure a good rf connection. We are now able to inject the magnetron's full 5 MW into the cavity.

An electron beam was injected into the accelerator while it was driven at the level 1 MW level. For this power level the maximum accelerated energy is expected to be 200 keV. The beam current emerging from the accelerator cavity with the rf off is shown in Fig. 9a and in Fig. 9b with the rf on. The buncher cavity was not energized. Notice that only 30% of the beam emerges from the cavity. This is to be expected from the sinusoidal variance of the rf wave. The rest of the beam is reflected before it reaches the end. Inclusion of the buncher will appreciably increase the transmission.

D. Harmonic Catcher

An rf-accelerated 300 keV beam at a current level of 10 mA was directed through the 11.57 GHz harmonic catcher cavity (the bunching diagnostic). Approximately 100 mW was emitted from the cavity. This power level can be expected to increase as the beam power is increased ($P \alpha I^2$ from Eq. 27) and as the buncher cavity is energized. The full operation current level of 1A can be expected to release nearly 1 kW as described previously in Sec. I.B. The initial experiments have been performed at low current levels for worker x-ray safety.

REFERENCES

1. W.B. Colson, Physics of Quantum Elec. 5, 157 (1978).

2. T.H. Kho and A.T. Lin, "Enhancement of Efficiency and Gain in Cyclotron Resonance Masers," submitted for publication to Phys. Fluids.

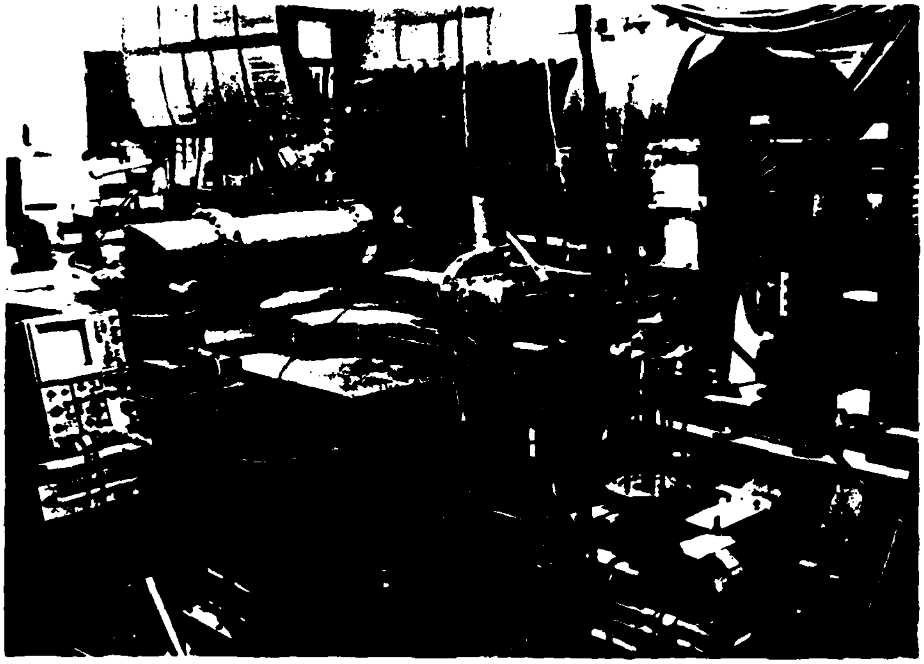


Figure 5 Photograph of accelerator system including magnetron with the rf cavity within a temporary solenoid.

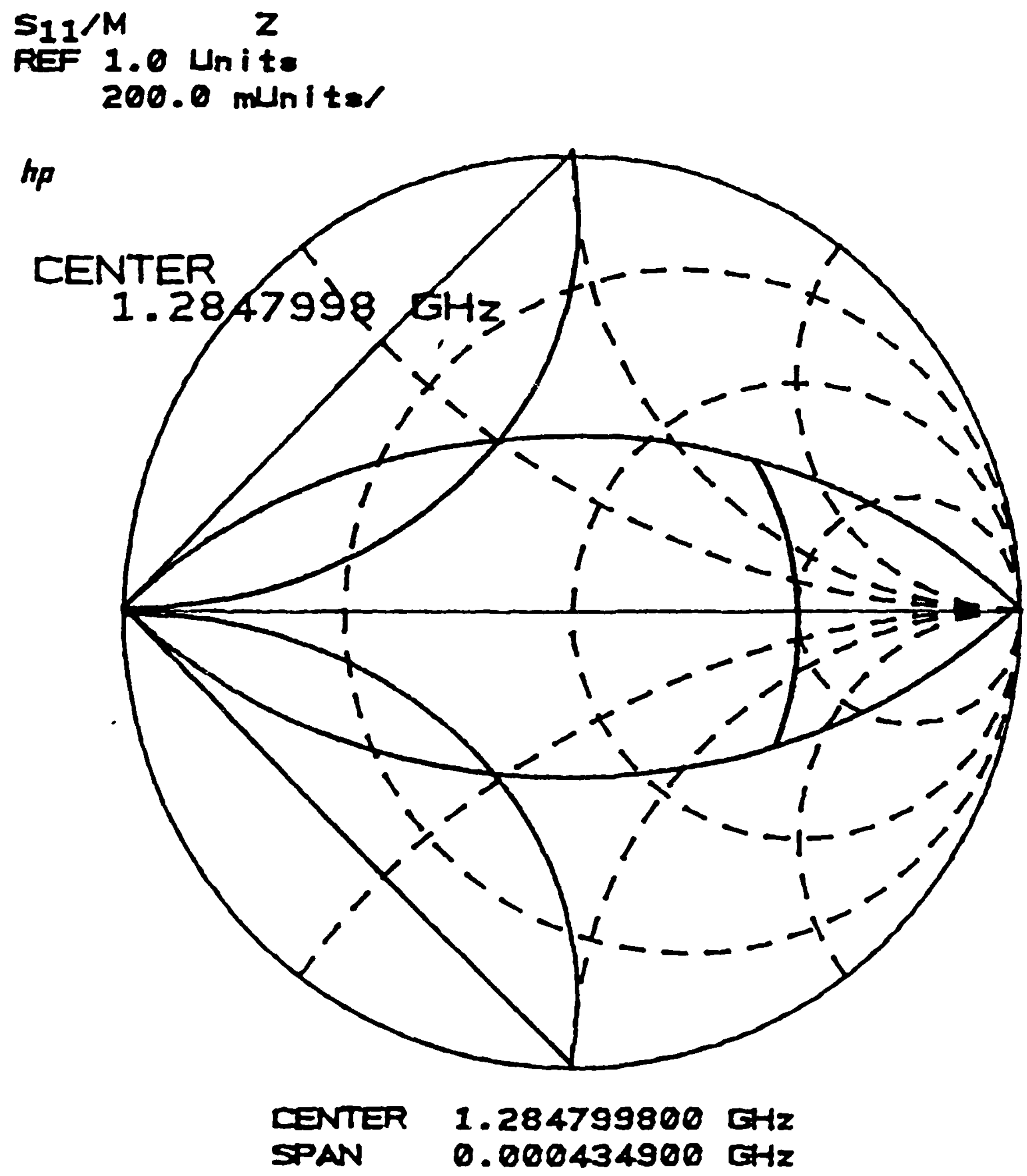


Figure 6 Smith chart measurement of accelerator's unloaded quality factor.

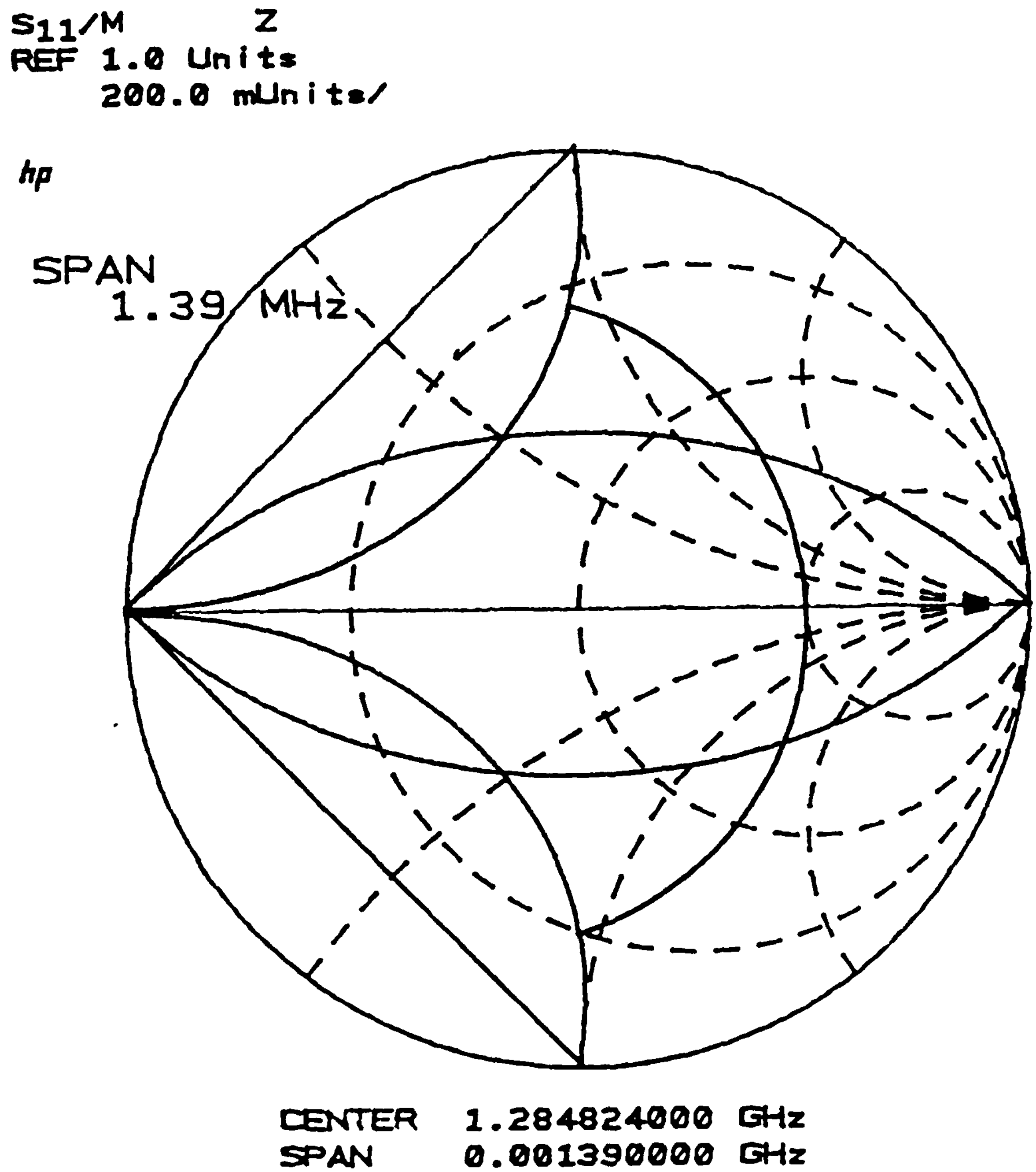


Figure 7 Smith chart measurement of accelerator's external quality factor.

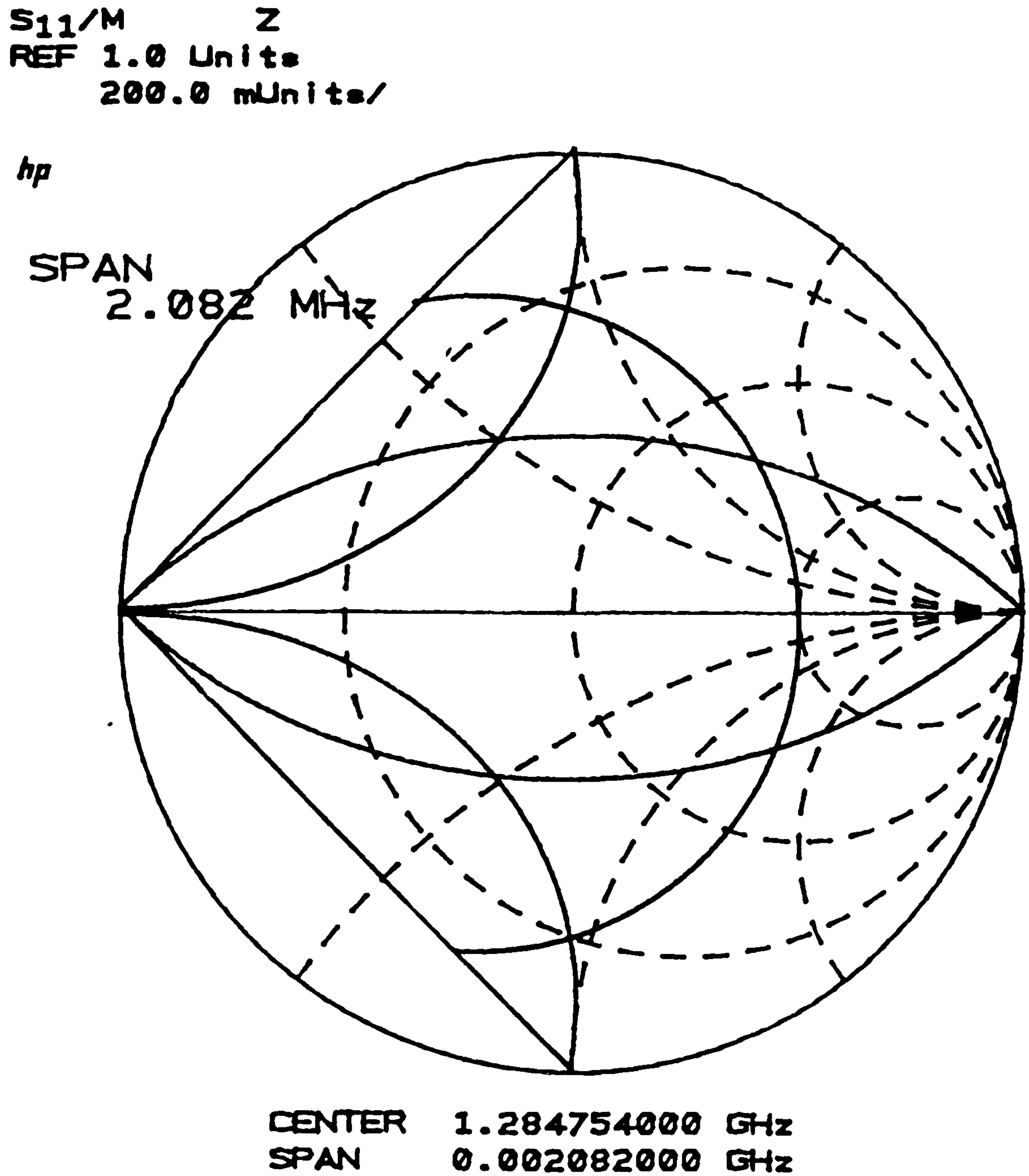


Figure 8 Smith chart measurement of accelerator's loaded quality factor.

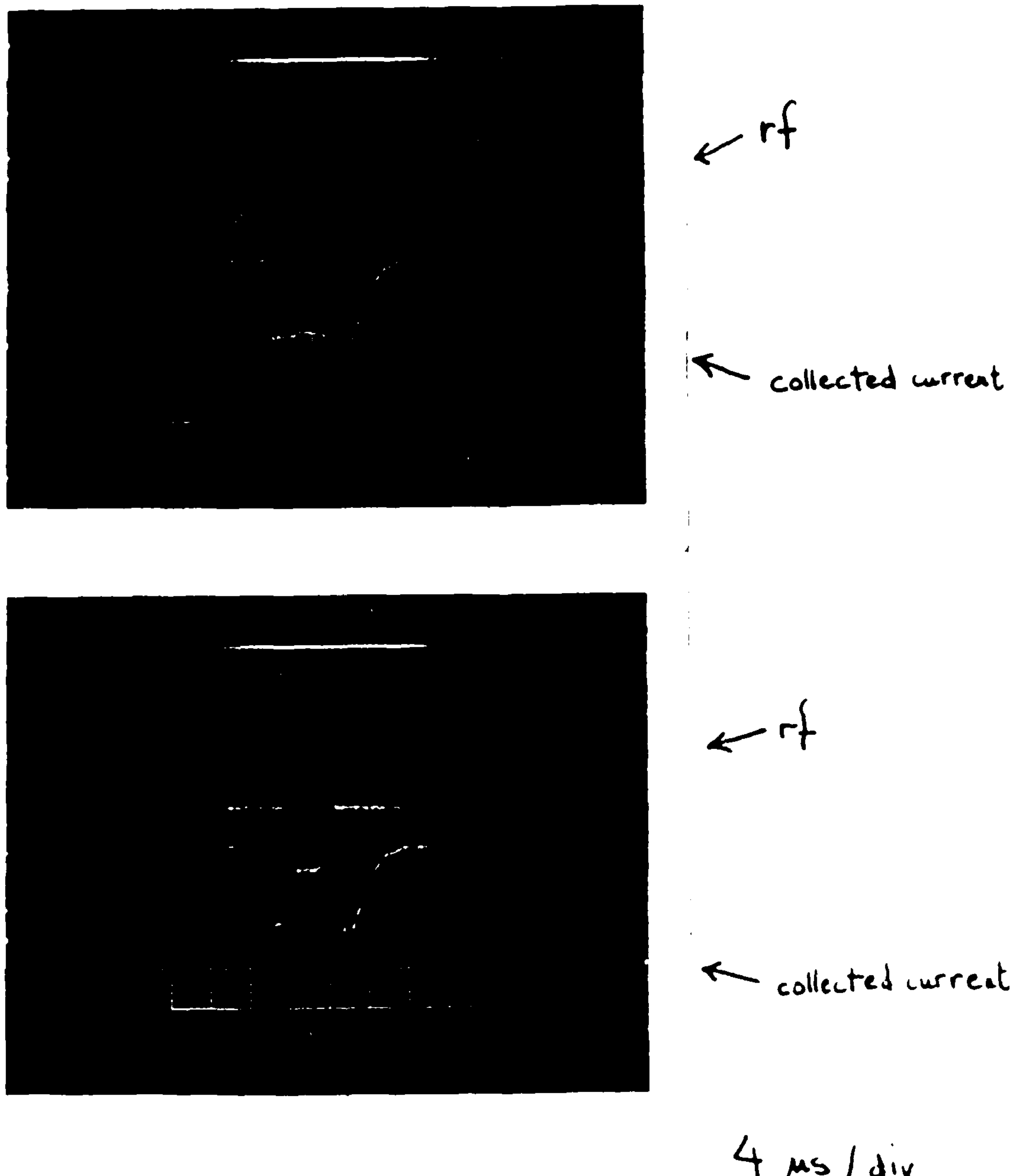


Figure Beam current emerging from the accelerator cavity with (a) the rf off and (b) the rf on.

END

12-87

DTIC