Beam Stability in DC-Pumped Cyclotron-Synchronous Wave Amplifiers

Electron beams of zero space-charge density are subject to beam expansion effects in axially symmetric dc pump structures.[1,2] This is because the off-axis drift motion of their electrons is the same as the electron motion in RF synchronous waves which are amplified by the structure. The expansion may lead to beam interception on the pump structure. To overcome this, focusing schemes have been proposed.[2] More importantly, the expansion seriously reduces the tube's theoretical figure of 100 per cent dc to RF conversion efficiency which is obtainable by using a filamentary paraxial beam by depression of collector potential. The efficiency reduction is proportional to beam thickness and is due to RF axial velocity spread produced on the beam by the phase dependent combination of transversally increasing dc motions and RF electron motions.

However, for beams of finite space-charge, continuous beam expansion can be eliminated. Thus, by removing the continuous coupling between dc and RF electron motions, high efficiency operation may be possible. A simple theory of beam stability is as follows. The radial motion of an electron from a shielded gun in the combined spatially-periodic paraxial pump field; the axial magnetic field $B_Z=\omega_c/\eta$, and the radial space charge field, which is assumed to have a spatially averaged plasma frequency ω_p, is determined by

$$\ddot{r}+r\frac{\omega_c^2}{4}\left[1-2\frac{\omega_p^2}{\omega_c^2}\right]-\eta\frac{\beta^2V_A}{2}r\sin\beta Z=0$$

where the pump potential varies axially as $V=V_0+V_A\sin\beta Z$.[1] If the apparent frequency at which electrons see the pump fields is ω, then $\beta Z=\omega t=2\phi$. Thus

$$\frac{d^2r}{d\phi^2}+r\frac{\omega_c^2}{\omega^2}\left[1-2\frac{\omega_p^2}{\omega_c^2}\right]-4\mu r\frac{\omega_c^2}{\omega^2}\sin 2\phi=0$$

where

$$\mu=\eta\frac{\beta^2V_A}{2\omega_c^2}\cdot$$

This Mathieu equation has solutions which are unstable (beam expansion) or stable (beam ripple), depending on the values of

$$\frac{\omega_c^2}{\omega^2}\left[1-2\frac{\omega_p^2}{\omega_c^2}\right]\quad\text{and}\quad 4\frac{\mu\omega_c^2}{\omega^2}\cdot$$

The stability limits are shown by the lines of Fig. 1. Instability occurs for all values of pump strength when

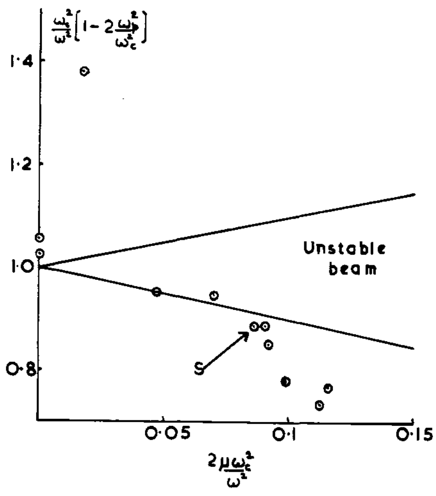

Fig. 1—Beam stability limits.

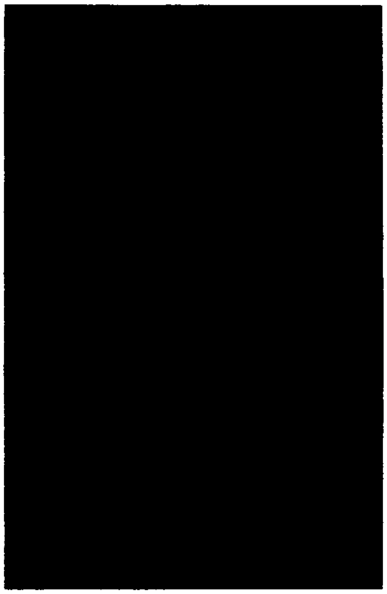

Fig. 2—Upper trace (a) current through aperture. Lower trace (b) current intercepted by aperture. Vertical scale (1 ma/divn). Horizontal scale, pump volts (210 volts/divn).

$$\omega=\omega_c\sqrt{1-\frac{2\omega_p^2}{\omega_c^2}}\,\cdot$$

This corresponds to electron pumping at the difference frequency of the "internal" electron frequencies

$$\frac{\omega_c}{2}\left[1\pm\sqrt{1-\frac{2\omega_p^2}{\omega_c^2}}\right].$$

Substituting practical values, shows that beams in cyclotron wave amplifying conditions ($\omega=\omega_c$), whose density is greater than about 0.1 of the Brillouin density ($\omega_p=2^{-1/2}\omega_c$), are stable in normal pump fields. More exact calculations for a Brillouin beam in wave amplification conditions show its beam edge ripple to be typically about ten per cent of beam radius.[3]

An experiment was performed on beam expansion in a twelve element electrostatic pump made from thin discs of 8.5 mm aperture diameter and 17 mm pitch. A shielded gun was used. Initially the magnetic field was 392 oersted giving a synchronous beam voltage of 1000 v for cyclotron wave amplification. By sweeping the pump voltage and monitoring current intercepted by a 1.5 mm diameter aperture, placed after the structure at a position of maximum beam expansion for one polarity of sweep, the onset of expansion could be determined. Fig. 2 shows that the current through the aperture (a) remains unchanged until the pump reaches 420 v, whereupon it rapidly decreases and aperture current increases (b). The central pip on the trace is due to leakage of secondaries back along the tube at zero pump voltage. By beam voltage and magnetic field variation, the stability limits can be plotted as a function of space change and pump strength. Beam densities are determined by the current passing through the aperture. Results principally occurred close to the lower stability line. Point S corresponds to three different synchronous conditions taken at 1000 v, 1200 v and 1400 v.

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J. C. BASS
Dept. of Elec. Engrg.
The University of Sheffield
England

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[1] J. C. Bass, "Microwave amplification in electrostatic ring structures," PROC. IRE (*Correspondence*), vol. 49, p. 1424; September, 1961.

[2] T. Wesselberg, and K. Blötekjaer, "A dc pumped amplifier using a space periodic magnetic field," PROC. IRE (*Correspondence*), vol. 50, p. 2513; December, 1962.

[3] J. C. Bass, D. C. Rickard and M. G. F. Wilson, "Theoretical and experimental investigations of dc pumped amplifiers," to be published in *Proc. IV Intern. Congr. on Microwave Tubes*, The Hague, Holland, Macmillan and Co., Ltd., London, England; 1962.

Laser Action in Singly Ionized Krypton and Xenon

Laser oscillation has been observed in pulsed krypton and xenon discharges on 21 wavelengths spanning the visible portion of the spectrum. All lines observed arise from transitions between levels of the singly-ionized state of the atoms (Kr^{II}, Xe^{II} spectra). The wavelengths and tentative level assignments are given in Table I for krypton and Table II for xenon. Oscillation between energy levels of ions has previously been reported for mercury[1] and argon.[2] The levels reported here are analogous to those observed in argon. The xenon transitions are all $s\to p$ or $s'\to p'$, while the krypton transitions are predominantly of this type, but include one $p\to d$ and two $p'\to d$.

The discharge tube, mirrors and pulse power supply used were the same as those described in Ref. (2), with the only change being the substitution of a large oxide cathode (from a Type 5C22 thyratron) for

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[1] W. E. Bell, "Visible laser transitions in Hg^+," *Appl. Phys. Lett.*, vol. 4, pp. 34–35; January 15, 1964.

[2] W. B. Bridges, "Laser oscillation in singly ionized Argon in the visible spectrum," *Appl. Phys. Lett.*, vol. 4, pp. 128–130; April 1, 1964.

TABLE I
KRYPTON LASER TRANSITIONS

Wave-length	Level Assignment	Relative Amplitude
4577.20	$5p'\ ^2F^0_{7/2} \rightarrow 5s'\ ^2D_{5/2}$	Weak
4619.15	$5p\ ^2D^0_{5/2} \rightarrow 5s\ ^2P_{3/2}$	Strong
4633.88	$5p'\ ^2F^0_{5/2} \rightarrow 5s'\ ^2D_{3/2}$	Weak (b)
4680.41	$5p\ ^2S^0_{1/2} \rightarrow 5s\ ^2P_{1/2}$	Moderate
4762.43	$5p\ ^2D^0_{3/2} \rightarrow 5s\ ^2P_{1/2}$	Strong (a)
4765.74	$5p\ ^4D^0_{5/2} \rightarrow 5s\ ^4P_{3/2}$	Strong (a)
4825.18	$5p\ ^4S^0_{3/2} \rightarrow 5s\ ^2P_{1/2}$	Moderate
5208.32	$5p\ ^4P^0_{3/2} \rightarrow 5s\ ^4P_{3/2}$	Strong (a)
5308.66	$5p\ ^4P^0_{5/2} \rightarrow 5s\ ^4P_{3/2}$	Weak (a)
5681.89	$5p\ ^4D^0_{5/2} \rightarrow 5s\ ^2P_{3/2}$	Strong
6470.89	$5p\ ^4P^0_{5/2} \rightarrow 5s\ ^2P_{3/2}$	Strong (a)
6570.07	$5p'\ ^2D^0_{5/2} \rightarrow 4d\ ^2F_{5/2}$	Weak (b)
6764.43	$5p\ ^4P^0_{1/2} \rightarrow 5s\ ^2P_{1/2}$	Moderate (a)
6870.85	$5p'\ ^2F^0_{5/2} \rightarrow 4d\ ^2P_{3/2}$	Weak (a)
7993.22	$5p\ ^4P^0_{3/2} \rightarrow 4d\ ^4D_{1/2}$	Moderate (a)

Notes:
(a)—Optimum pressure of the order of 0.010 torr.
(b)—Optimum pressure of less than 10^{-4} torr.
All others—Optimum pressure of the order of 0.001 torr.

TABLE II
XENON LASER TRANSITIONS

Wavelength (Å)	Level Assignment
4603.028	$6p\ ^4D^0_{3/2} \rightarrow 6s\ ^4P_{3/2}$ (a)
5044.92	$6p'\ ^2P^0_{1/2} \rightarrow 6s'\ ^2D_{3/2}$
5261.95	$6p'\ ^2D^0_{3/2} \rightarrow 6s'\ ^2D_{3/2}$
5419.15	$6p\ ^4D^0_{5/2} \rightarrow 6s\ ^4P_{3/2}$ (a)
5971.13	$6p'\ ^2P^0_{3/2} \rightarrow 6s'\ ^2D_{3/2}$
6270.82	$6p'\ ^2F^0_{5/2} \rightarrow 6s'\ ^2D_{3/2}$

Note:
(a)—Strongest lines.

those cathodes used with argon. The discharge tube had a diameter of 4 mm and an active length of 107 cm. Three sets of multilayer dielectric-coated mirrors were used to give high reflectivity over the range 4000 Å to 8000 Å. The maximum available discharge current of 40 A was used for most of the work; only at higher-than-optimum pressures was a clear maximum in output power found with less than 40 A discharge current. Optimum pressure for some of the lines was very low, less than 10^{-4} torr, producing a rather unstable discharge. Unlike argon, addition of a buffer gas (helium, neon or argon) degraded the output in power and number of lines oscillating. It was possible, however, to obtain simultaneous oscillation on all the lines of krypton and xenon within the range of the mirrors used when both gases were present in amounts near their individual optimum pressures.

None of the lines reported here were observed in the afterglow; all lines began oscillating during the exciting pulse (variable 0.5 to 7 μsec) with a delay from the leading edge of the exciting pulse to the threshold of oscillation of ~0 to 6 μsec, depending on the particular transition and the gas pressure. However, for a given transition and pressure, the delay was independent of exciting pulse length or amplitude.

No accurate gain measurements were made with the krypton and xenon transitions; however, the stronger lines would continue to oscillate when a reasonably clean quartz plate was inserted into the cavity and varied about ±20° from the Brewster's angle. The estimated gain from this test is about 10 per cent per meter for the stronger lines.

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WILLIAM B. BRIDGES
Hughes Research Labs.
Malibu, Calif.

Microwave Amplification with Superconductors

Experiments which demonstrated a nonlinear inductance and frequency conversion in superconducting films at 54 kMc[1] have been repeated at lower frequencies. Parametric amplification and oscillation have been observed. The "modified dielectric resonator"[1] when cooled to 2°K yielded 11 db of net gain at 6.06 kMc. The resonator, illustrated in Fig. 1, was operated in the "doubly-degenerate mode,"[1] *i.e.*, the signal, pump and idler frequencies were within the same resonance band and spaced in an arithmetic progression. The developed idler power was approximately equal to that of the signal, as expected.

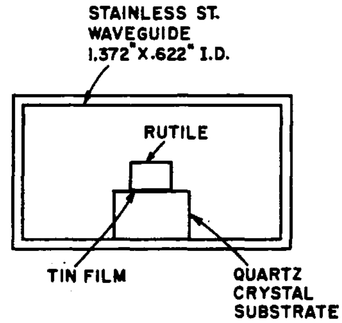

Fig. 1—The modified dielectric resonator mounted in a waveguide.

When operating under high gain conditions the device was unstable at low signal levels and, hence, was probably functioning as a locked oscillator. Efforts are now directed toward obtaining linear small-signal output-input characteristics.

The pump power required for amplification was only 0.2 microwatt, which is orders of magnitude less than that for varactors. The unusually low power requirement is partially due to the very small loss factor of a superconductor and to the minute film volume. Low power requirements are advantageous in parametric digital circuits and in millimeter-wave amplifiers, where power is at a premium. A low pump power, however, implies a low signal saturation level. The power handling capacity should increase markedly at higher frequencies and at operating temperatures closer to the critical.[2]

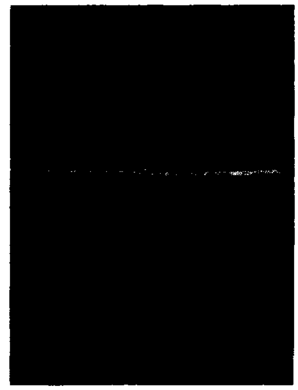

Fig. 2—Output and input spectra of the superconducting parametric amplifier.

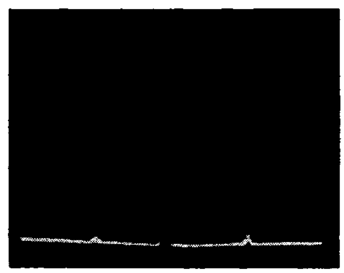

Fig. 3—Output spectrum of the superconducting parametric oscillator.

Fig. 2 illustrates the output and input spectra of the amplifier. The lower trace shows pump and signal inputs of −37 dbm and −65 dbm, respectively. The upper trace is the device output and illustrates a larger signal, a reduced pump and three new frequencies. The frequency immediately to the left of the pump is the idler. The two smaller pips are attributed to higher order mixing processes in the film. The available power gain is measured as the amount by which the input signal power must be reduced to restore the output signal pip to the level in the lower trace.

With the signal input turned off and the pump parameters properly adjusted, parametric oscillations were observed. These occurred in pairs, symmetrically spaced about the pump frequency. A pair of these oscillations together with the reflected pump frequency is shown in Fig. 3.

No accurate measurement of amplifier bandwidth was attempted. The voltage gain-bandwidth product, however, appears to be of the order of 1 Mc. The bandwidth may be improved by increasing temperature, coupling, or operating frequency. Furthermore, broad-band traveling-wave structures utilizing distributed films appear feasible.

An analysis of the modified dielectric resonator[2] shows that the bandwidth can be improved, in principle, by decreasing the film thickness. In a very thin film, however, uniformity and even continuity may be lost. The thickness of the films used in this research is estimated to be 250 Å which represents an attempt at a compromise between

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[1] A. S. Clorfeine, "Nonlinear reactance and frequency conversion in superconducting films at millimeter wavelengths," *Appl. Phys. Lett.* vol. 4, pp. 131–132; 1964.
[2] A. S. Clorfeine, to be published.