A HIGH POWER X-BAND RELATIVISTIC KLYSTRON

T.J. Davis, E. Chojnacki, and J.A. Nation
Laboratory of Plasma Studies and School of Electrical Engineering
Cornell University, Ithaca, NY 14853-5401

Abstract

Relativistic klystrons have been proposed as an r.f. drive for future high gradient accelerator structures. Presented are details of experiments in which a 400 keV, 250–500 Amp electron beam is propagated through X-band TM_{020} cavities to demonstrate high beam energy, high frequency klystron operation. A magnetron supplies microwave power to the initial cavity for amplification. Profiles of the downstream r.f. magnetic field have indicated that space charge oscillations dominate the klystron beam behavior. Previous small signal experiments are correlated to present high power results in order to compare gain measurements, beam loading effects, and output r.f. pulse quality.

Introduction

The next generation of r.f. linear accelerators is proposed to have beam energies of order 1.0 TeV. High frequency operation decreases the required length of r.f. linacs, but also increases damaging longitudinal and transverse wake field effects. The operating frequency range of future upgraded linacs has therefore been compromised to the 10–30 GHz range [1]. In order to drive the future accelerating structures to acceptable field gradients, further high power amplifier development is needed. A likely component for such development is short pulse length, high energy electron beam technology.

In the past two years, rigorous development into the extension of normal klystron amplifiers to high peak power, high frequency operation has begun to address these source requirements [2]. Klystron amplifiers, whether in the form of longitudinal relativistic klystrons or gyroklystrons [3], offer substantial d.c. to r.f. conversion efficiency with excellent phase stability. A further increase in efficiency of a longitudinal klystron tube may be accomplished using a two-beam accelerator approach [4], an attractive scheme because it eliminates the cost and complexity of driving each accelerator section with a separate module.

An ongoing experimental program at Cornell University is examining the physics of short pulse, high frequency relativistic klystrons. The goals of this program are not only to generate and extract high power r.f., but also to provide physical insight to the mechanisms of relativistic beam modulation at high frequencies and breakdown processes in short pulse, high power klystron devices.

Beam Dynamics

Qualitatively, a relativistic klystron operates upon similar principles as a typical klystron tube; an electron beam is velocity modulated by an r.f. electric field in the initial cavity, drifts to form a density modulation, and couples through these electron bunches to an output cavity which extracts r.f. power. Relativistic mass effects will tend to degrade this process by increasing the optimal bunching distance and introducing asymmetries over the r.f. cycle in the velocity modulation. However, in practice, all moderately intense beams are dominated by collective processes which reduce the location of maximum bunching to

$$L_{max} = \frac{\pi}{k_s - k_f}$$

where k_s, k_f are the wavenumbers for the slow and fast space charge waves, respectively. The dispersion relation for both azimuthally symmetric space charge modes is contained in the equation

$$\frac{k_\perp J_1(k_\perp a)}{hJ_0(k_\perp a)} = \frac{I_0(hb)K_1(ha) + I_1(ha)K_0(hb)}{I_0(hb)K_0(ha) - I_0(ha)K_0(hb)}$$

where a is the beam radius, b is the guide radius, and

$$h^2 = k_z^2 - \frac{\omega^2}{c^2}$$

$$k_\perp^2 = \left(\frac{\omega^2}{c^2} - k_z^2\right)\left(1 - \frac{\omega_p^2}{\omega_b^2}\right)$$

$$\omega_b = \omega - k_z v_d \quad \text{and} \quad \omega_p^2 = \frac{ne^2}{\gamma^3 m\epsilon_0}.$$

The space charge wave density and velocity variations are initialized by the field conditions at the input cavity and vary spatially in the subsequent drift region. Cavities placed downstream of the initial cavity will modify the amplitude of the wave perturbations, further enhancing the density modulation on the beam. The final stage of any klystron is the extraction of power from the output cavity or other resonant structure, which optimally couples to the maximal system density perturbation.

Experimental Configuration

The experimental schematic is illustrated in figure 1. The field emission foilless diode is driven by a Marx-Blumlein configuration and the resulting pencil beam is characteristically 400 keV, 250–500 Amps depending upon the actual diode geometry. The 3.2 mm radius beam is injected directly into a 6.4 mm radius drift tube with focusing provided by an 8 kG solenoidal magnetic field. Device behavior is independent of variations in this guiding magnetic field over the range 5–

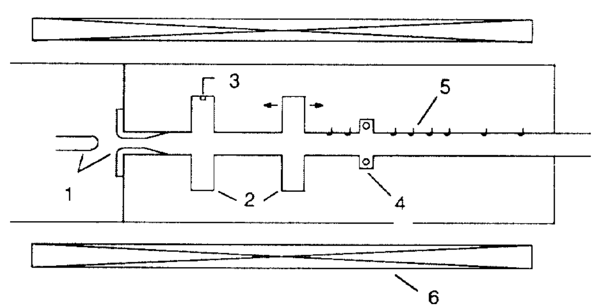

Fig 1. Experimental schematic. (1) Foilless diode, (2) TM_{020} cavities, (3) magnetron input, (4) Rogowski coil, (5) $\dot{B}_\theta$ loops, (6) confinement coil.

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10 kG. After a short drift region, the beam enters the initial or input cavity which is driven at resonance by an X-band magnetron. Following the initial cavity the modulated beam may be passed through subsequent cavities or directly to a diagnostic section containing a Rogowski coil and a row of magnetic field probes. These $\dot{B}_\theta$ probes, monitored using microwave crystal detectors, sample the fringing r.f. field associated with the forming electron bunches and thus provide a relative measure of the extent of beam modulation.

The cavities were designed to operate in the TM_{020} mode and oscillate at 9.0 GHz. Cavity field levels are also monitored with magnetic field loops, and provide the basis for system gain measurements since no power extraction has yet been attempted. Unloaded cavity quality factors have typically been 500–1000.

Experimental Results

Varying beam current, input cavity power levels, and cavity transit angles has provided a large experimental database. The current experimental parameters are listed in table 1.

Input Cavity Drain

Upon passage of the beam, the input cavity is drained by action of the beam convective dissipation term

$$\langle P_{diss} \rangle = \langle \int_V J \cdot E \, dV \rangle$$

where $\langle\rangle$ indicates a time average over the r.f. cycle. This dissipation term is primarily due to variations in particle transit times across the r.f. cycle. The power dissipation decreases the cavity Q to values less than 10 for a 10 mm gap cavity, but makes only slight changes to the Q of a 3 mm gap cavity.

Initial experiments were limited to 0.1–1.0 kW of r.f. drive in the cavity, corresponding to axial electric fields of up to 1 MV/m. For recent experiments, the magnetron is coupled directly from waveguide to the cavity and delivers 25 kW of r.f. power, providing maximum electric fields of 5.4 MV/m. Although during beam passage this field level may decrease by a factor of two or more depending upon beam current, no change in reflected power from the cavity is observed. This is further evidence that resistive beam loading, and not a breakdown phenomena, is the primary cause of power drain.

Frequency (GHz)	9.00
Beam Radius (mm)	3.2
Guide Radius (mm)	6.4
Beam Energy (keV)	400
Beam Current (A)	250-500
Cavity Radius (mm)	29.4
Cavity Gap Length (mm)	10.0
Unloaded Q's	
Cavity 1	900
Cavity 2	3000
Cavity 3	900
Nominal E_z (MV/m)	
Cavity 1	4.0
Cavity 2	12.0
Cavity 3	70.0

Table 1. Current klystron operating parameters.

Loop Profiles

Early experiments were intended to map the modulated beam profile after only a single input cavity. The axial profile was accomplished using the drift tube $\dot{B}_\theta$ loop probes, and was found to be independent over the range of input cavity electric fields up to 1 MV/m. The profiles for two different beam conditions is shown in figure 2. For these electric field levels, simple ballistic focusing would create a maximum perturbed beam density farther than one meter downstream. However, calculations including the collective beam effects described earlier agree within a factor of two with the experimental data. Collective behavior in klystron geometries has previously been demonstrated with more intense beams at lower frequencies [5].

Up to about 20 cm downstream of the cavity, the r.f. loop signals were constant amplitude across the beam pulse width. After this distance, the signals become peaked over only portions of the pulse, possibly due to the differences in space charge wave characteristics over the changing beam voltage–current conditions. A typical loop trace 16 cm downstream of the input cavity is shown in figure 3. The frequency stability of the modulation process was demonstrated by heterodyning the loop traces with a local oscillator. The resulting beat waveform, displayed in figure 4, shows that coherent modulation is produced uniformly over the entire beam pulse width.

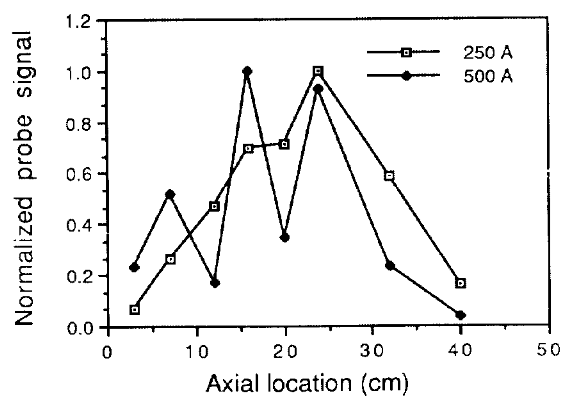

Fig 2. Profile of magnetic probe signal strength vs. axial position. Signals are normalized to the maximum at each current condition.

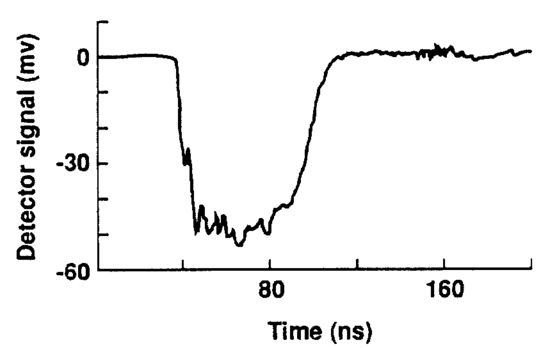

Fig 3. Characteristic loop trace 16 cm downstream of the input cavity.

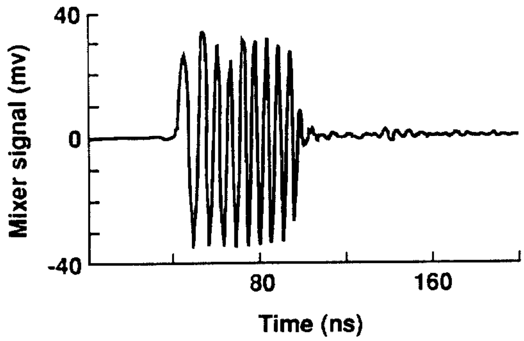

Fig 4. Loop signal heterodyned with a 9.14 GHz local oscillator. Beat waveform demonstrates excellent frequency and amplitude stability over the entire beam pulse width.

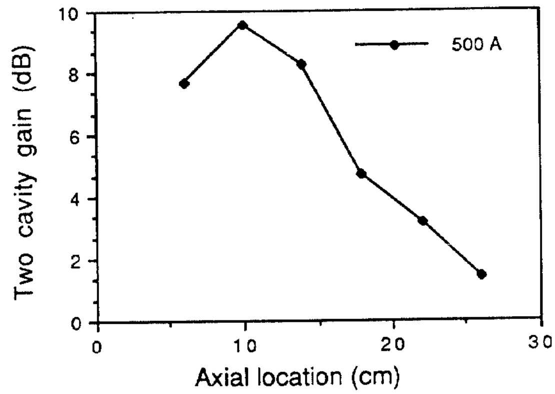

Fig 5. Axial profile of two cavity gain for 500 A beam current.

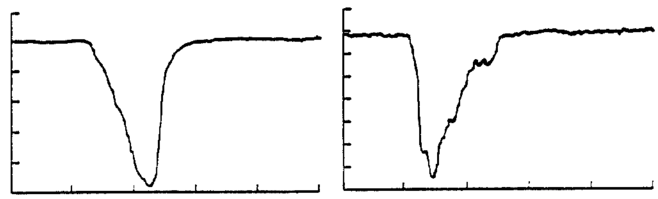

Fig 6. Second cavity r.f. pulse shapes for 250 A current, 1 kW drive (left) and 500 A current, 25 kW drive (right).

Multiple Cavities

Multiple cavity experiments then demonstrated typical klystron operation. At low input cavity drive power, surveys of second cavity signal level vs. downstream position showed a similar axial dependence as the loop profiles, independent of cavity gap length. Although not amplitude stable over the entire beam pulse width, a maximum gain of 15 dB was recorded for 10 mm gap cavities.

Recent high power experiments (25 kW input drive power) have not closely correlated with low power klystron operation. A downstream survey of cavity signal strength vs. axial location at 500 Amps beam current is shown in figure 5 to have a single maximum at 10 cm. This differs from the loop profiles shown in figure 2 for the same beam conditions, and is possibly due to a change in space charge wave boundary conditions at the high electric field, large cavity gap as opposed to the low electric field, small cavity gap loop profiles. Nevertheless, the current operating klystron has demonstrated a two cavity peak gain of 10 dB and a three cavity peak gain of 25 dB, where gain has been measured by the relative field strengths in the cavities.

Pulse Shortening

Downstream cavity pulse shapes are consistently peaked over portions of the beam pulse width. Two output cavity waveforms are compared in figure 6 for a vastly different set of operating conditions. These cavity waveforms were taken at positions where magnetic loop probes displayed full pulse width waveforms (compare with figure 3). Such pulse shortening has plagued other relativistic klystron experiments [6], and is often attributed to breakdown or beam loading effects in the cavities.

Multipactoring or other breakdown processes are highly unlikely in this case, given the low field levels and large gap spacings. Also unlikely is the effect of finite cavity filling times, since many traces have fast rise times and beam loading has been shown to be significant in the initial cavity. One possible explanation is enhanced energy deposition from the input cavity into the leading edge of the pulse, which causes transient loading in the downstream cavities and correspondingly alters the cavity resonance.

Conclusions

A satisfactory explanation of most klystron results to date has been provided by a collective beam description. Space charge waves are established according to the boundary conditions and field levels at the initial cavity, and are modified at subsequent cavities. The actual wave–cavity coupling process is inherently nonlinear, and efforts are underway to predict the particle–field interactions in the cavities using a particle–in–cell code. Beam loading and pulse shortening have been of particular interest in the experiments. A large cavity gap, although optimal for breakdown prevention, allows for large beam loading which considerably decreases the initial cavity modulating electric field. This beam loading may also be contributing to pulse shortening in the downstream cavities, which is apparently not due to any breakdown phenomena and is exhibited over all operating regimes of the klystron. The future experimental program is geared towards alleviating pulse shortening and enhancing high power klystron operation.

Acknowledgements

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