HIGH-POWER, MILLIMETER-WAVE SOURCE DEVELOPMENT AT LOS ALAMOS NATIONAL LABORATORY*

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Abstract

High power mm-wave rf sources are an enabling technology for ultra-compact linear accelerators. Los Alamos is aggressively pursuing high power mm-wave (100-300 GHz) source development for accelerator and other applications. Our ultimate goal is a 0.5-MW, 300-GHz traveling-wave source with 1 μsec pulse lengths, using a micro-fabricated planar slow-wave structure and sheet electron beam. Reaching this goal will take several intermediate steps. The first step, being done this year, is to drive a 100-GHz slow-wave structure with a low-voltage (10 kV), low-perveance (0.5 μperv) pencil beam, interacting in the *n*=-1 mode (backward wave). This experiment will verify our scaling laws and benchmark our simulation codes, and will use the same type of ridged-waveguide slow-wave structure that we plan to use for the high-power 300 GHz design (which will operate in the *n*=0 forward mode). A key issue associated with a structure of finite width is transverse-field flatness, which we are addressing by capacitively tuning the waveguide ridges. We will present cold test results and describe our mode code DETER, our particle-in-cell code TUBE, and present gain results from them.

1 BACKGROUND AND MOTIVATION

The millimeter wavelength region of the electromagnetic spectrum is relatively undeveloped partly because of the lack of of high power sources between 100 GHz and 0.5 THz, where free space wavelengths vary from 3 mm down to about 0.5 mm. An emerging need for low power, high gain, and particularly low cost RF amplifiers around 100 GHz for high bandwidth communications has caused us to initiate a study of traveling wave amplifiers. If high power sources are available at these frequencies, then it may also be possible to build ultra-compact linear accelerators for specialized applications.

Interest in high power mm-wave technology is stimulated by recognizing the importance of the confluence of several emerging sub-technologies. The first of these technologies is the demonstration of stable sheet electron beam propagation. Two-plane focusing of sheet beams is reasonably well understood having been driven by the design of wigglers for free-electron lasers (FELs). Work at SLAC and the University of Wisconsin shows that PPM and PQM configurations propagate stable sheet beams. Secondly, electron beam physics developed by the accelerator community has led to a good understanding of asymmetric beam emittance, quadrupole focusing, and halo generation minimization. Finally, advances in microfabrication technology such as LIGA offer the possibility of producing monolithic RF structures with tightly controlled dimensional tolerances on the scale of a millimeter or less with surface finishes compatible with low-loss at W-band. Most importantly, the economy of scale possible with microfabrication offers the promise of low cost.

2 GAIN CALCULATIONS

The main design goal is to make the electron beam synchronous with a large amplitude space harmonic in a traveling wave structure. Our initial experiment will be at 100 GHz with a beam at 10 kV, and is intended to be a technology step toward our final goal of 300 GHz and 140 kV.

A previous analysis of planar, rippled waveguide traveling-wave tubes showed large gain for nominal structure and beam parameters [1]. Extending the dispersion relation to achieve synchronism with a 10 kV beam at 100 GHz we get the dispersion relation shown in Fig. 1. This curve shows the dispersion relation between a k of zero and 3 π/λ with a period λ of 0.75 mm. The region between k=0 and π/λ is the n=0 fundamental mode; the region between π/λ and 2π/λ is the n=-1 backward mode; and the region between 2π/λ and 3π/λ is the n=+1 forward mode. The RF wave at 100 GHz will have components of all these space harmonic modes and the actual RF field will be a linear superposition of these modes.

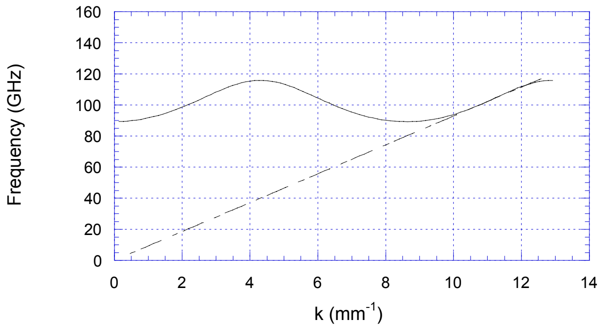

Fig. 1. Waveguide dispersion relation showing synchronism between a 10 kV electron beam and the n=1 space harmonic at 10 GHz.

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* Work supported by the Los Alamos National Laboratory Directed Research and Development program, under the auspices of the U.S. Department of Energy.
LANL Publication No. LA-UR-02-4864.

The n=0 fundamental mode in the region between 0 and π/λ could be made synchronous if the vane height was large and the vanes were extremely close together. Although possible to build with LIGA fabrication, these constraints can be relaxed somewhat by considering the higher order n=1 mode. In this mode we can expect reasonable gain with a bandwidth of 10-20%. This was verified by using the code SUPERFISH to calculate the dispersion curve. The field plot in Fig. 2 shows the π/2 mode. In this calculation the period is 0.73 mm, gap half-height is 0.87 mm and step height is 0.38 mm. The SUPERFISH dispersion curve along with the 10 kV beam line is shown in Fig. 3. This curve although similar to the theoretical curve in Fig. 1 shows the effect of nonideal coupling.

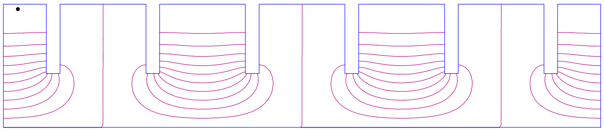

Fig. 2. SUPERFISH simulation of nominal 100 GHz geometry, showing π/2 mode.

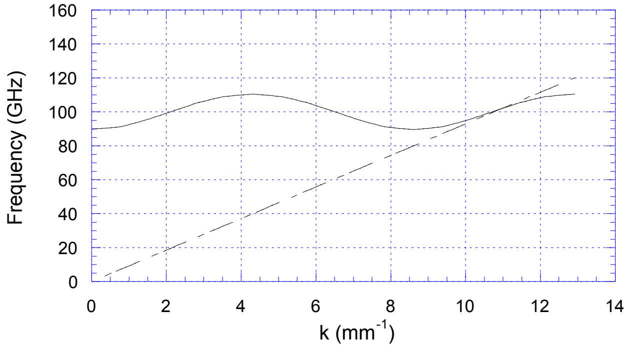

Fig. 3. SUPERFISH dispersion curve showing wide bandwidth *n*=1 interation with 10 kV beam.

The code DETER was used to solve the dispersion relation both with and without beam [2]. DETER is based on solving the dispersion relation by finding roots of the equivalent matrix of the space-harmonic coefficients, after using boundary conditions. DETER is shown to agree well with SUPERFISH results, Fig. 4.

The space-harmonic mode amplitudes are shown in Table 1. We find that the mode amplitude for the n=-1 is larger than any of the forward modes except for the fundamental.

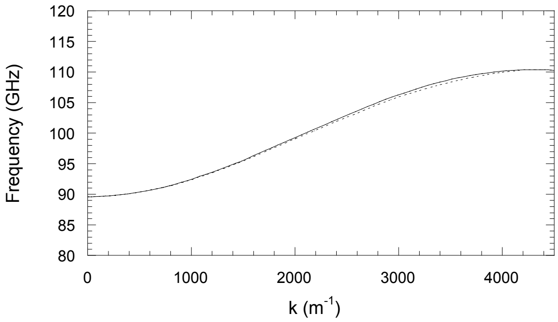

Fig. 4. Comparision of SUPERFISH and DETER calculations of the disperion curve. The solid line is from the SUPERFISH results and the dashed line is from DETER.

TABLE 1. Mode Amplitudes for *n*=1 interaction.

Mode	Complex amplitude
-4	(9.21e-6,6.07e-4)
-3	(-7.17e-3,2.50e-2)
-2	(0.00426,0.004955)
-1	(-0.129,0.0593)
0	1
1	(0.0233,0.0107)
2	(4.86e-2,5.66e-2)
3	(2.49e-4,8.66e-4)
4	(4.38e-6,-2.88e-5)

Focusing on the 10 kV experiment, we used DETER to estimate the gain of the n = -1 interaction with a 10 kV, 0.5 A beam in a 0.5 cm wide structure. The gain as a function of frequency is shown in Fig. 5. The gain is very high over the entire bandwidth of the slow wave structure. This design is the basis for the 10 kV experiment.

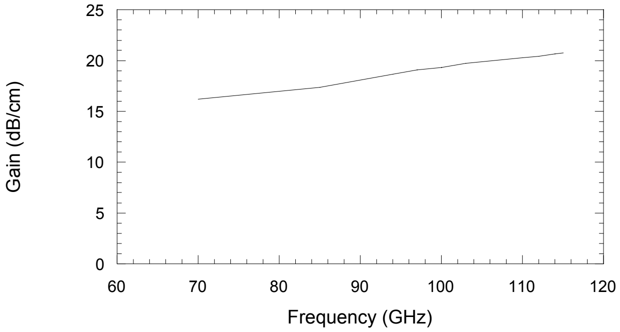

Fig. 5. Gain for *n*=-1 interaction for nominal 100 GHz geometry and 0.5 A, 10 keV electron beam.

In addition, the planar particle-in-cell code TUBE [3] has been used to study rf mode propagation, gain, and saturation for this interaction for both the n=0 and n=1 modes. In Fig. 6, we see the axial electric field on axis for the nominal 100 GHz, n=1 case. The Fourier decomposition of the fields is seen in Fig. 7. The results are in reasonable agreement with the DETER results in Table 1.

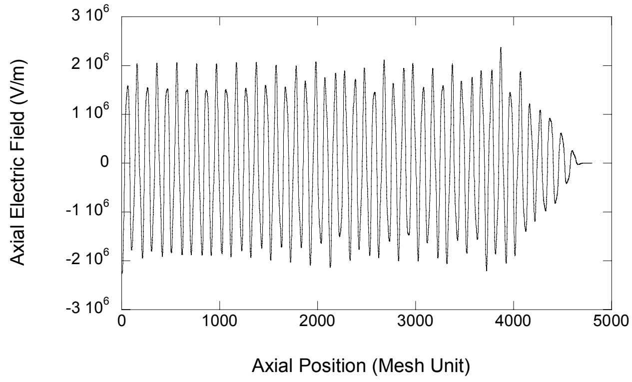

Fig. 6. Axial electric field for PIC simulation of nominal case, 3 nsec simulation time (72000 time steps).

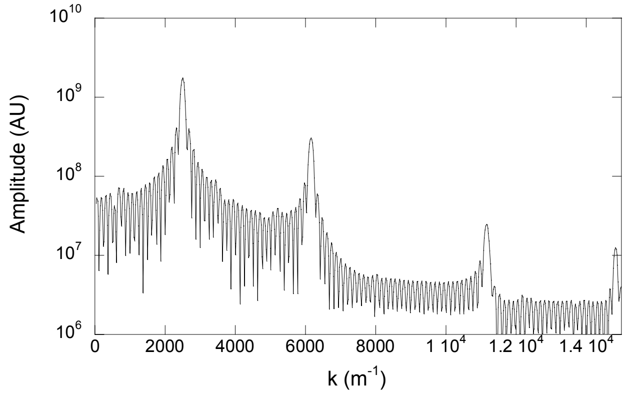

Fig. 7. Spectrum of modes as seen in TUBE:
n=0 mode is at about 2500 m^{-1},
n=1 mode is at about 11200 m^{-1},
n=-1 mode is at about 6200 m^{-1},
and n=-2 mode is at about 14800 m^{-1}.

3 EXPERIMENT AT 10 KV

The hardware is being assembled for a 10 kV, 100 GHz experiment. To minimize the initial cost the TWT is not being built as a vacuum assembly; instead, the tube RF structure, shown in Fig. 8, will be installed in a large vacuum chamber. The electron gun and slow wave structure are mounted on a vacuum flange as shown in Fig. 9. The slow wave structure is surrounded by a PPM stack for beam focusing. The hardware assembly is almost complete and testing will begin shortly.

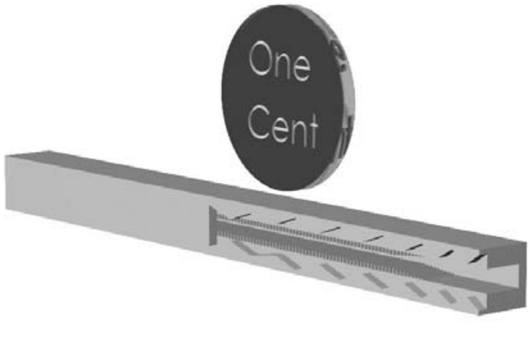

Fig. 8. Nominal 100 GHz structure for 10 kV experiment. The entire structure is 6 mm by 6 mm by 75 mm long, with 0.5 mm period. Input and output waveguides will be run inside the top and bottom structures.

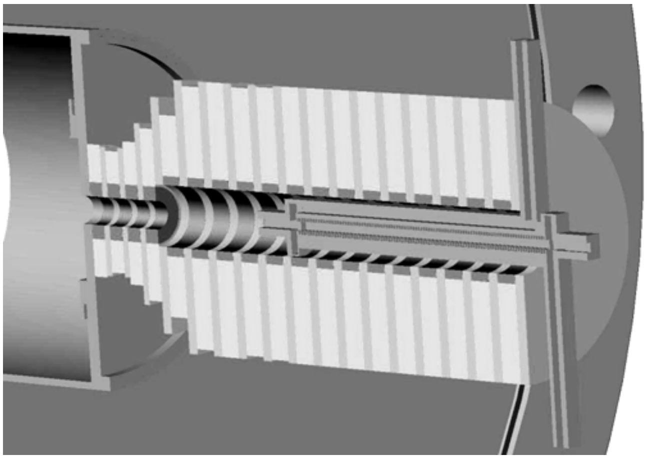

Fig. 9. Electron gun and slow wave structure surrounded by PPM stack are mounted on a vacuum flange and installed in a vacuum chamber. Input and output waveguides appear on right.

4 SUMMARY

We have examined several design options for ridged waveguide traveling wave tube amplifiers. We have chosen the n=-1 backward mode for an experiment at 10 kV because it has a higher gain than the n=1 mode and reasonable bandwidth. Although the highest gain occurs for the n=0 mode, at 10 kV the resulting structure has a very short period. An experimental TWT has been designed and fabricated. Testing will begin soon.

5 REFERENCES

[1] Carlsten, B. E., *Phys. Plasmas*, **8**, 2702 (2001).
[2] Carlsten, B. E., "Modal Analysis and Gain Calculations for a Sheet Electron Beam in a Ridged Waveguide Slow-Wave Structure," accepted for publication by *Phys. Plasmas.*
[3] Carlsten, B. E. , *Phys. Plasmas*, **9**, 1790 (2002).