SLAC – PUB – 4221
February 1987
(A)

DESIGN OF A WIGGLER-FOCUSED, SHEET BEAM X BAND KLYSTRON*

K. R. Eppley, W. B. Herrmannsfeldt and R. H. Miller
Stanford Linear Accelerator Center
Stanford University, Stanford, CA 94305

Abstract

An X band klystron using a sheet beam and wiggler focusing was simulated using the $2+\frac{1}{2}$ dimensional particle in cell code MASK.[1] Simulation of the rf cavities was by means of the port approximation used in modelling of standard klystrons.[2] The wigglers, which would need permanent magnets to achieve the required field strengths, were modelled using an idealized analytic expression with an exponential rise and a linear taper superimposed on a sinusoidal variation. Cavity locations and tunings were varied for maximum output power. Beam voltage and current were also varied to explore the effect on efficiency. Both an idealized laminar beam and a more realistic beam from a gun design code were studied. For a voltage of 200 kV and current of 20 amp per linear cm efficiencies of approximately 50% were calculated.

Introduction

The rf power for a future collider should be at a substantially higher frequency than the SLAC frequency of 2856 MHz. Among the advantages of the higher frequency are higher gradients before encountering the breakdown limit, and lower stored energy which greatly impacts both capital cost and operating cost of a large machine.[3] Recent studies at SLAC have tended towards the range of frequencies between 3 and 4 times the SLAC frequency of 2856 MHz.

Scaling conventional klystrons to such high frequencies would reduce the output power to only a few megawatts, since the beam current must be reduced to fit through a smaller structure. This paper describes an alternate klystron design, which is to use a sheet beam or a hollow beam, thus permitting high total currents without increasing the current density to the point that space charge effects impair the efficiency. It was recently pointed out that a very similar concept was proposed by R. Kompfner at Oxford in 1947,[4] who called the device the "traveling wave klystron."

The focusing of sheet beams or hollow beams was developed by Sturrock.[5] Ordinary solenoids cannot be used for such a beam, but an arrangement of dipole magnets that causes the electrons to "wiggle" periodically, in the plane of the beam, provides very strong focusing. The focusing mechanism is the same as that encountered by an electron beam passing through the wiggler magnet for a free electron laser; the beam is focused towards the median plane of the wiggler by the edge fields of the alternating dipole magnets. The focusing action is only in the direction normal to the median plane, but appropriate shaping of the fields at the ends of the dipoles can also provide edge focusing of the sheet beam. This technique is also commonly applied to free electron laser wiggler magnets. A schematic arrangement of the components is shown in Fig. 1. As noted, the focusing action is quite strong because it does not alternately focus and defocus; each edge field focuses. The usual constraints of focusing limits and stop bands of periodic focusing apply, but with reasonable dipole fields of about 0.1 tesla, the currents that can be transported greatly exceed what can be realistically injected. The focusing requirements will be found to depend mostly on effects of transverse rf fields in the klystron.

The initial goal was to design a 100 MW source of X-band power at 11.42 GHz. The nominal starting design parameters for this device were 200 kV beam voltage and 1000 amperes total current in 50 linear cm. These numbers are probably not optimal; however, it would be difficult to use much higher voltages without making the output cavity gap too wide (due to breakdown considerations) for good coupling. Likewise, it would be difficult to get much higher current densities from a conventional gun.

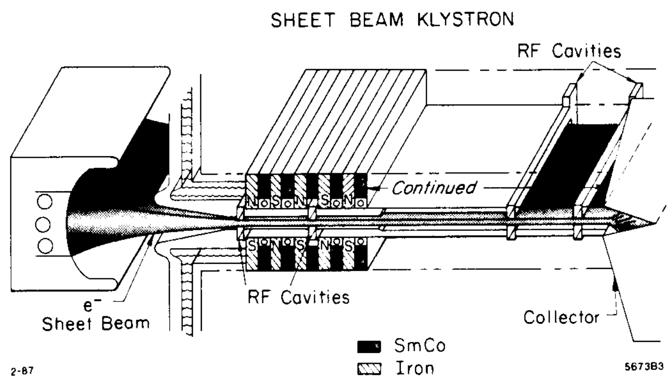

Fig. 1. Schematic of the sheet beam klystron showing drift tube, cavities, and wiggler magnets.

Design Study

Starting from these nominal values, we have used MASK to design the rf interaction region to obtain maximum power output. The rf cavities are modelled using the port approximation described by S. Yu.[2] We impose a given voltage and phase as a boundary condition. The code then calculates the induced current from the beam dynamics (once steady state has been reached) whence the desired cavity impedences can be obtained.

The input beam was first taken to be purely laminar with zero transverse velocity. Parameter studies were made varying the cavity locations and voltages to optimize efficiency. Beam voltage and current were then varied to explore their effect on efficiency.

The wiggler field was modelled using an idealized analytic expression derived from a vector potential which was a product of a sinusoid in the x_1 direction (parallel to the beam) and a hyperbolic sine in the x_2 direction. More freedom was obtained by adding a product function $f(x_1)$ in the x_1 direction, which

* Work supported in part by the KEK–SLAC Collaboration and by the Department of Energy, contract DE – AC03 – 76SF00515.

Presented at the Particle Accelerator Conference, Washington, D.C., March 16-19, 1987

could allow a linear ramp and/or an exponential rise. While this is no longer an exact solution of Laplace's equation, and thus includes a non-physical current source, it is not a bad approximation as long as the function $f(x_1)$ varies slowly with respect to the wiggler period. While these wiggler expressions will not correspond exactly the fields produced by the permanent magnet/iron assemblies, they are a reasonable first approximation to the magnet design made using the code POISSON.

Initial calculations were made using an input cavity, one idler cavity, and an output cavity. Because of the potential problem of feedback if the non-cutoff TE modes were excited, it seemed desirable to keep the gain as low as possible. We assumed that input power of the order of 10 to 20 kW at X band could be obtained, for example from traveling wave tubes if klystrons were not readily available. This corresponds to a voltage of about 5 kV on the input cavity. (The precise value will depend on what tuning and external Q are assumed.)

The location and voltage of the second cavity control the gain but do not appear to be very critical in determining the maximum rf current downstream (which controls the efficiency). The gain of the second cavity determines the optimum drift length to the output stage. The voltage and location for the second cavity were picked to produce optimal bunching in a length that seems reasonable for construction and simulation considerations.

It was found that higher efficiency could be obtained by the addition of another cavity, corresponding to the penultimate cavity in a standard tube, although the optimal voltage for this cavity is low compared to that in a standard klystron for the same beam voltage. The voltages and locations of the penultimate and output cavities were varied to optimize efficiency.

Figure 2 shows the locations for the cavities of a four-cavity wiggler focused klystron. The figure shows the electron distribution taken as a snapshot at a particular instant within an rf cycle. This example is from a run in which both the top and bottom of the klystron are simulated, thus making further simulations possible in which the effects of asymetric construction can be examined.

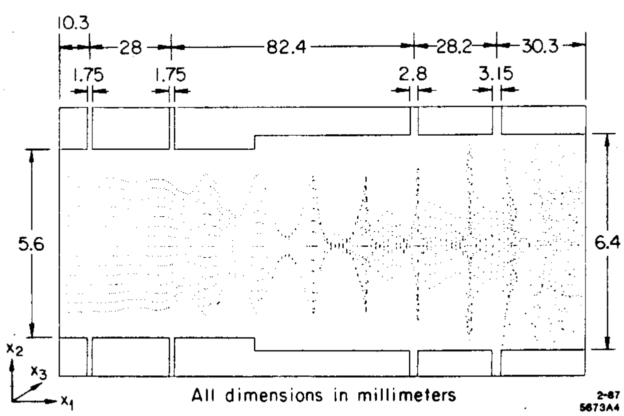

Fig. 2. Electron position-space distribution (not to scale) for the wiggler focused klystron with an initially laminar beam. RF ports are shown as gaps in the blocks. All dimensions are in mm.

The phase of cavity 1 was arbitrarily set to 0. For cavities 2 and 3, it was assumed that the Q would be high enough that the phase difference between voltage and induced current would be about $\pi/2$. For the output cavity, the phase was varied to optimize efficiency. The strength and slope of the ramp of the magnetic field were also varied to produce optimum bunching with minimal interception before the output cavity, and thus maximum output power.

Voltages and phases are shown in Table 1 for the optimum efficiency case. The efficiency came to about 48%, or 96 MW for 200 MW of beam power from a 50 cm wide klystron.

Table 1. Cavity Voltages and Currents For the Laminar Beam

Cavity	RF Gap Voltage (Phase)	Induced Current (Phase)
1	4750 (−.10)	6.8 (1.85)
2	28840 (2.21)	39.9 (.90)
3	56210 (−1.40)	716. (−2.93)
4	259500 (−.50)	774. (−.04)

Beam Voltage and Current Parameter Study

Using the laminar input beam and tapered wiggler fields, the voltage and current were varied to explore their effect on efficiency. The cavity voltages, etc. were optimized for maximum efficiency for each point (although not as much time was spent as in the initial study, so the true optimum may be slightly higher). Efficiency was not sensitive to beam current with fixed voltage up to a factor of three times the nominal current (Fig. 3). At this point efficiency began to drop. Efficiency only increased slightly in raising the voltage to 300 kV, but dropped to about 41 percent at 100 kV (with constant perveance). The required magnetic field was roughly linear in beam current. There was a small increase in required magnetic field with higher voltage.

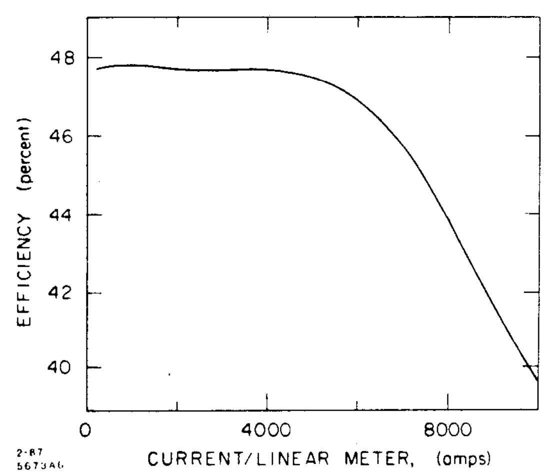

Fig. 3. Efficiency versus current, 200 kV beam energy.

It is unclear what factors limit the efficiency of the wiggler focused klystron. For a standard klystron the efficiency would be expected to increase more with lower perveance than was observed here. We note that for both cylindrical and flat klystrons the bunching is much better in the part of the beam nearer the walls, but in the cylindrical case the poorly bunched beam near the axis contains only a small fraction of the total current, while for the flat case it contains nearly half. The variation in bunching might be due in part to variable rf fields across the drift tube. However, reducing the drift tube by a factor of four in height (with corresponding reduction in beam current and size) did not improve the efficiency. It is possible that the variation in focusing from the transverse rf and dc magnetic fields across the drift tube are responsible for the variability of the bunching. It is also possible that if more time had been spent on optimization in the low perveance simulations the efficiency might have been increased further.

Effect of Realistic Input Beam

A more realistic input condition was obtained by using the electrostatic EGUN code to calculate the beam distribution at the input to the drift tube. The gun calculation assumed no magnetic field, so MASK used a magnetic field which was initially zero and turned on exponentially. Another modification was to increase the field just before the penultimate cavity to compensate for the transverse momentum impulse from that cavity. The voltages and currents are shown in Table 2. For this design the x_1 locations of the cavities were as in the laminar case, but some variation in the x_2 size of the drift tube was made. The final efficiency ended up to be similar to the laminar case, about 50%. These findings are tentative because the modelling of the turn-on of the magnetic field at the beam input was a rather crude approximation of the field that would be produced by the actual magnets.

Table 2. Cavity Voltages and Currents for the Realistic Beam

Cavity	RF Gap Voltage (Phase)	Induced Current (Phase)
1	4490 (−.10)	5.2 (1.69)
2	28900 (2.51)	47.7 (1.06)
3	83640 (−1.12)	759. (−2.69)
4	260400 (−.40)	832. (.14)

Radio Frequency Cavity Considerations

The initial concept of the rf cavity design was that the cavities should operate at cutoff so that the field would not have any variation is strength along the length of a cavity. We now believe that tolerances, and the close proximity of many modes at cutoff, make this solution impractical. A better solution was suggested by P. McIntyre[6] who would use traveling wave cavities which create a bunch that is tilted with respect to the direction of motion of the electrons. We now believe that a small shear in the pattern of rf currents on the beam is not a problem, and that traveling wave cavities can be used, even placed on a line normal to the beam direction, provided that the phase velocity of the desired mode is the same for each cavity. These traveling wave structures are actually tuned resonant rings, with a directional coupler for the input and the output cavities. Except for the resonant ring, the device now closely resembles the sketches from Kompfner from 1947.

The use of traveling waves in the interaction cavities causes an additional complication to the electron dynamics, due to the transverse magnetic fields that must accompany the traveling wave. These magnetic fields are normal to the plane of the sheet beam and accordingly act to deflect the electron orbits within the plane of the sheet beam. The transverse magnetic field and the longitudinal electric field have their maxima in the same place, and the direction of the magnetic field is such that the deflection on the beam is in the direction opposite to the power flow for particles which are phased to give up energy to the rf fields. For the parameters of the 100 MW klystron being studied here, and for waveguide with a group velocity of $v_g = 0.7c$, the magnetic field is about 0.1 tesla in the output cavity. This is clearly not negligible and it thus becomes mandatory to study the klystron with a three dimensional code in order to adequately simulate the process in the output traveling wave cavity. For the particles in the bunch that is being decelerated, it is possible to largely compensate for this deflection by adjusting the fields in the wiggler magnets so that the electrons enter the output cavity at an appropriate angle.

Conclusions

A wiggler-focused sheet beam klystron with efficiencies of about 50 percent and power around 200 MW per linear meter appears theoretically attainable. If gun design permits substantially higher perveance without increasing the drift tube size, up to a factor of three higher power may be possible without much loss in efficiency.

References

1. A. Palevsky and A. T. Drobot, "Application of E-M P.I.C. Codes to Microwave Devices," in Proceedings, Ninth Conference on Numerical Simulation of Plasmas, paper PA-2, Northwestern University, Evanston, Illinois, June 30-July 2, 1980.
2. S. Yu, "Particle In Cell Simulation of High Power Klystrons," SLAC/AP-34, September 1984.
3. P. Wilson, "Future e^+e^- Linear Colliders and Beam-Beam Effects," SLAC-PUB-3985, May 1986, presented at Stanford Linear Accelerator Conference, June 2-6, 1986.
4. J. Lawson, private communication.
5. P. Sturrock, Stanford Microwave Laboratory Reports 595 and 596, May 1959.
6. P. McIntyre, private communication.