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TITLE: THE DEVELOPMENT OF AN ANNULAR-BEAM, HIGH POWER FREE-ELECTRON MASER FOR FUTURE LINEAR COLLIDERS

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The Development of an Annular-Beam, High Power Free-Electron Maser for Future Linear Colliders

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Abstract

Work is underway to develop a 17 GHz free electron maser (FEM) for producing a 500 MW output pulse with a phase stability appropriate for linear collider applications. We plan to use a 500 keV, 5 kA, 6-cm-dia annular electron beam to excite a TM_{02} mode Raman FEM amplifier in a corrugated cylindrical waveguide. The annular beam will run close to the interaction device walls to reduce the power density in the fields, and to greatly reduce the kinetic energy loss caused by beam potential depression associated with the space charge which is a significant advantage in comparison with conventional solid beam microwave tubes at the same beam current.

A key advantage of the annular beam is that the reduced plasma wave number can be tuned to achieve phase stability for an arbitrary correlation of interaction strength with beam velocity. It should be noted that this technique for improving phase stability of an FEM is not possible with a solid beam klystron. The annular beam FEM provides the opportunity to extend the output power of sources in the 17 GHz regime by well over an order of magnitude with enhanced phase stability. The design and experimental status are discussed.

Introduction

Future linear colliders require microwave power sources in the 10-30 GHz frequency range with output powers of at least several hundred megawatts. The klystron has historically been the source of choice for accelerator applications. The output power from a klystron though does not scale favorably as one goes to higher power and higher frequency, simply because klystrons operate in the fundamental mode and the power density becomes extremely high. As the frequency increases, a klystron shrinks in volume resulting in a higher energy density and a corespondingly high electric field in the structure. Problems such as rf breakdown and microwave pulse shortening become serious and ultimately limit device performance. For output power levels above several hundred megawatts, new approaches are needed for microwave power generation. One example is a microwave tube based on a large diameter annular electron beam instead of the small diameter solid beam used in a klystron [1]. The large diameter beam has several advantages. More power can be transported in an annular beam because the space charge limiting current in an annular beam is higher than in a solid beam of the same voltage and current. At the same time, the perveance per square in an annular beam can be similar to the perveance in an efficient, solid beam microwave tube. This reasoning leads us to the conclusion that microwave tubes with large diameter annular electron beams may be well suited for the extreme peak power requirements demanded by future linear collider applications.

Free-electron lasers and FEMs have demonstrated high peak power and extraction efficiencies. An FEL or FEM offers the possibility of a way to avoid this fundamental power density limitation by operating in a higher-order mode in a larger microwave electrodynamic structure. In 1992, Conde and Bekefi tested an FEM that produced 61 MW at 33 GHz at 27% efficiency [2]. This tube was driven by a 750 kV, 300 A, 30 ns, solid electron beam. The goal of our work is to extend this work to high power (1/2 GW) at 17 GHz by using an annular electron beam.

FEM Phase Stability

Phase stability has been examined in detail by Carlsten [3] for an axial interaction FEM with an annular beam operating in the exponential growth regime. These results are extensively discussed in the reference and the reader is referred there for a detailed discussion. Accelerator applications require phase stability on the order of 5° of phase, and advanced accelerator applications such as bunch compression [4] and short wavelength FELs require phase stability of 1° or less [5]. Phase noise in an FEM arises from fluctuations in beam voltage and current, magnetic field strength, and other tube parameters. The largest source of phase noise is typically the fluctuation in beam voltage. The electron beam voltage in a microwave tube operationg between 1/2 and 1 MV can, with care, be controlled to 1/4%. Measurements and simulations of FEL phase stability range from 20^{o} to 40^{o} of shift per percent of voltage variation [6, 7]. This level of stability is inadequate for advanced accelerator applications. The principle mechanism producing the phase noise is the variation in transit time of the electron beam through the microwave tube due to variations in beam energy. Additionally in an FEL the growing mode's phase velocity depends on beam current, plasma frequency, and the interaction strength between the beam electrons and the RF field.

It can be shown that when an annular beam is used in a Raman regime FEM, a correlation between interaction strength and beam velocity is not needed to find a first-order phase and gain stable operating condition. By introducing the effect of the space charge wave, a detuning can be found in the Raman regime that leads to phase stability for an arbitrary correlation of interaction strength with beam velocity. The gain of the autophase condition can be kept large by proper manipulation of the plasma reduction factor. This is only possible if the electron beam is annular and close to the beam pipe wall. In Fig. 1 we plot the derivative of the phase evolution of the RF mode with respect to beam energy in the exponential growth regime versus the normalized space-charge wave number β_q^2, for the case of $\gamma = 2$, frequency $= 13$ GHz, and a ripple period of 6 cm. Phase stable operation is achieved with a 5 kA beam current at approximately the predicted space-charge wavenumber.

Axial FEM Experiment

The construction of an experiment is underway to demonstrate the concept of an annular beam, Raman regime, axial FEM operating in the TM_{020} mode. An axial free-electron laser interaction between an annular electron beam and a TM_{0n} mode is desirable because the resulting particle orbits are inherently more stable than those in conventional transverse FELs with helical wigglers [8]. The net transverse force on an electron integrated over a wiggle period can be made to vanish by the proper choice of waveguide radius. The axial FEL interaction for a synchronous particle is shown in Fig. 2. In this device, an annular beam interacts with the field of a mode in a circular waveguide. The radius of the waveguide is periodically rippled which causes the mode to radially expand and contract as it propagates down the waveguide. The ripple amplitude is only a few percent of the average waveguide radius, allowing the rf mode to conform adiabatically to the change in waveguide radius. The annular beam is located at the radius coresponding to the zero of the axial electric field of the TM_{02} waveguide mode with a radius equal to the mean radius of the rippled waveguide. When an electron is at the position of the smallest waveguide radius, the axial electric field at that location decelerates the electron. As the electron travels to the region of larger radius, the rf phase slips by the electron. When the electron is at the position of maximum waveguide radius, 1/2 of the rf wavelength has slipped by resulting in a sign change of the mode's fields. At the same time the electron has switched from one side of the null in axial electric field to the other side, resulting in another sign change. The net result is that the electric field is still opposing the electron motion. This interaction is equivalent to the interaction of a transverse-coupling FEL except that the RF field is wiggled, instead of the electrons, to achieve synchronism. One should note that this is a fast-wave interaction, not a slow wave one. A dispersion curve is plotted in Fig. 3 for a generic waveguide with small perodic ripples. As the ripple amplitude goes to zero, the forbidden zone disapears and the dispersion curve reverts to that of an unperturbed waveguide. A slow wave interaction would occur at point "A" where the phase velocity is below the velocity of light. In our experiment, we are operating at point "B" because the RF wavelength is much shorter that the waveguide ripple period.

A particle-in-cell simulation of the FEM using the code ISIS was done. A coaxial geometry, associated with an early design, is shown in Fig. 4. The RF power propagates in the TM_{020} mode and is driven at 17.1 GHz. The inner conductor wall is at the the axial null of the TM_{02} electric field. There are 71/2 ripples with a length of 12 cm each, and the beam is confined with a 0.5 T axial magnetic field. There is very clear axial bunching in the 60-100 cm region along the direction of propagation.

Our FEM configuration is shown in Fig. 5. A 600 kV annular beam is supplied by a stainless steel field-emission cathode. The nominal beam radius is about 2.8 cm with a thickness of 4 mm. The beam drift pipe has a 3.6 cm mean radius. An input section has been designed with 6-fold symmetry on the waveguide feeds. This was done to reduce the number of high order modes that, if generated, will be able to propagate down the overmoded waveguide and cause beam disruption. The input section is followed by the rippled wall structure with about 15 ripple periods. The ripple wavelength is 3.5 cm. Folllowing the electrodynamic structure is a circular waveguide with several directional couplers built in to measure power in the desired TM_{020} mode. A calorimeter will be located at the end of the tube to absorb all the microwave energy regardless of mode. The comparison between the directional couplers and the calorimeter should give us information on mode purity.

Conclusions

An annular beam, Raman regime, free electron maser can be viable candidate as the power source for future linear colllider applications where extremely high peak powers are required. An annular beam, TM_{02} device is auto- phase stable because the space charge wave propagation constant can be adjusted for an arbitrary correlation of interaction strength and beam velocity. Such a device is being asembled for high power testing.

Acknowledgements

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Figure captions

Fig. 1. Sensitivity of phase to beam energy for medium gain and low energy ($g = 2$) as a function of space charge wavenumber.

Fig. 2. Axial electric field orientations for a synchronous particle when the particle reaches the centers of the ripples in r-z geometry.

Fig. 3. Generic dispersion relation for a periodic waveguide with small perturbations.

Fig. 4. Particle-in-cell simulation of coaxial geometry showing electron beam with strong axial bunching.

Fig. 5. FEM experimental configuration.

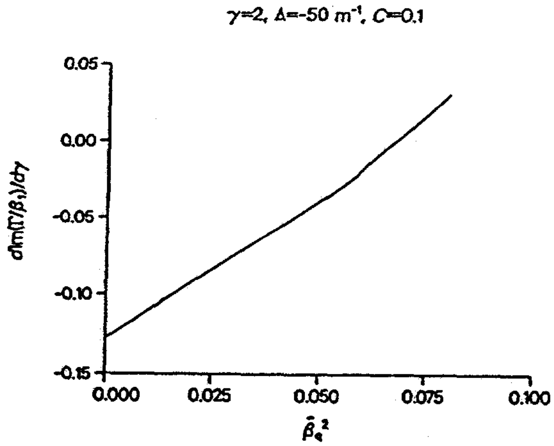

Fig. 1. Sensitivity of phase to beam energy for medium gain ($C=0.1$) and low energy ($\gamma=2$), as a function of space-charge wavenumber, for a detuning $\Delta=-50\,\mathrm{m}^{-1}$.

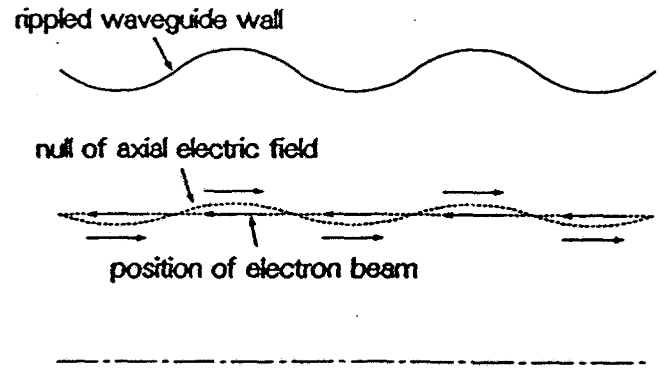

FIG. 2 Axial electric field orientations for a synchronous particle when the particle reaches the centers of the ripples in r-z geometry.

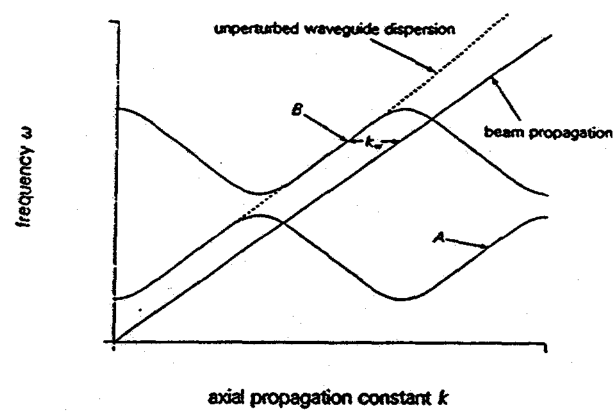

Fig. 3 Generic dispersion relation for a periodic waveguide with small perturbations.

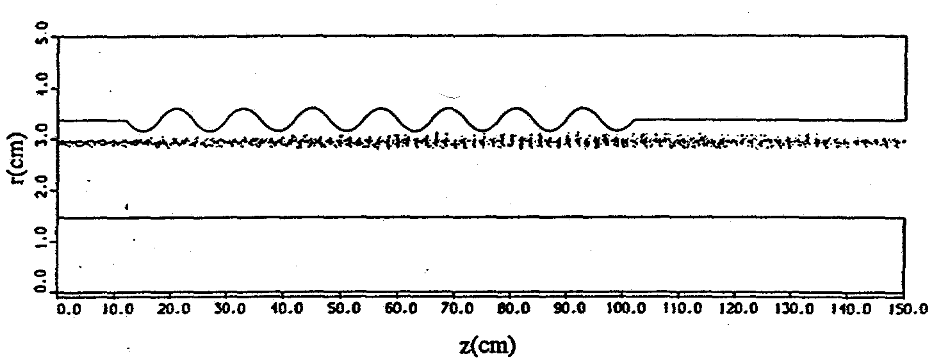

Fig. 4 Coaxial geometry used for ISIS simulation. The electron beam is injected at a radius of 2.92 cm into a larger rf field, and shows strong axial bunching.

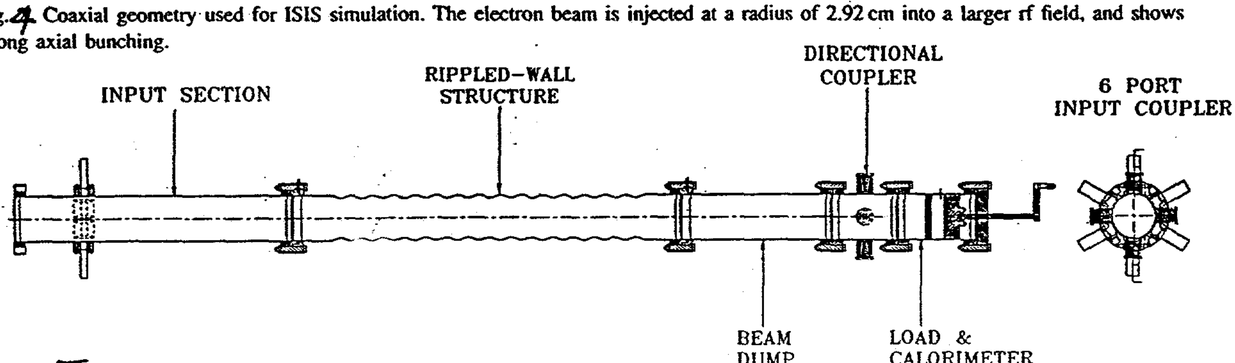

FIG. 5