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NEW CONCEPTS IN MICROWAVE SOURCES FOR e^-e^+ SUPERCOLLIDERS*

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Abstract

The realization of e^-e^+ supercolliders will require advances in technology including the development of X-band microwave amplifiers with pulse energy > 60 J. Candidate microwave amplifiers include klystrons, lasertrons, free electron lasers (FEL's), and gyrotrons; gyrotron amplifiers employing a multicavity gyroklystron configuration appear advantageous at $\lambda = 3$ cm. Measurements on a 50 kW, 1 μs gyroklystron show phase jitter < 0.75^0 indicating compatibility of this type of amplifier with collider requirements. The University of Maryland is currently devloping an X-band, TE^0_{01} mode gyroklystron driven by 500 keV, 160 A, 2 μs electron beam pulses; combining this tube with a TE^0_{01} binary pulse compression circuit under development at SLAC could produce 475 MW, 120 ns microwave pulses which imply the feasibility of achieving linac accelerating fields in the range 100-200 MV/m.

Introduction

Interest in e^-e^+ colliders with each particle having energy in the range > 300 GeV has placed a premium on developing linac technology which might achieve large values of the accelerating gradient E_a. With $E_a = 200$ MV/m, the total length of two 300 GeV linacs would be 3 km, equal to the length of the present 50 GeV SLAC accelerator.[1]

A number of linac scaling studies have been carried out,[2-4] and include the dependence of E_a on rf frequency, ω, and on peak rf power per accelerator feed, P_f, as

$$E_a \sim \hat{P}_f^{\,1/2}\,\omega. \qquad (1)$$

Thus, a premium is placed on achieving high $\hat{P}_f$ and especially high ω. However, if ω is increased too much, deleterious effects occur such as excessive energy spread due to increased wakefields. A reasonable compromise appears to be $\omega/2\pi = 10$ GHz; i.e., three to four times the present SLAC frequency.

A 10 GHz linac would require $\hat{P}_f$ in the range 300-600 MW to achieve $E_a = 100$-200 MV/m. The corresponding length of the rf pulses would be $\tau_p = 100$-200 ns ($\tau_p \sim \omega^{-3/2}$). Thus, the feasibility of developing microwave amplifiers in X-band (8.2-12.5 GHz) with pulse energy ≥ 60 J is an issue relevant to e^-e^+ supercolliders. To be compatible with linac operation, the amplifier should have good phase stability ($\lesssim 1^0$) and high gain ($\gtrsim 50$ dB). The microwave generators which are candidates for this development are briefly surveyed in the next section.

Klystrons, Lasertrons, FEL's and Gyrotrons

Studies of an experimental klystron amplifier at SLAC have demonstrated 150 MW output power in 1 μs pulses at a frequency of 2.87 GHz.[5] A double gap output cavity was used to reduce gap voltage gradient to increase efficiency to 51%. A scaling of this device to 10 GHz could be accomplished by reducing the linear dimensions of the klystron circuit and its beam tunnel in proportion to the wavelength, λ, while maintaining the 475 kV accelerating voltage on the electron gun. Since the dc electric fields are near the breakdown limit at the electrodes of the 2.87 GHz klystron, the anode-cathode spacing could not be reduced in the X-band device. With the electron gun operated in the space charge limited regime, current density would then be unchanged while the area of the beam tunnel would be reduced as λ^2. Thus, current and power would also fall as λ^2, and 150 MW at 2.87 GHz would scale to 12 MW at 10 GHz. Of course some more advantageous scaling scheme might be found, and X-band klystrons deserve further consideration.

The lasertron is a new type of microwave tube which uses the same type of output cavity as a klystron but produces a bunched electron beam by illuminating a photo-emissive cathode with short bursts of laser light. Such a device gives good control over the shape of the electron bunches and can have unusually high efficiency.[6] Furthermore, a dc voltage may be applied to the electrodes eliminating the requirment for a modulator. An S-band lasertron is presently under study at SLAC. There may be difficulty; however, in increasing the laser light pulse rate to achieve X-band operation.[7]

Studies which have been carried on during the past two decades on microwave generation with relativistic electron beams have led to two fast wave microwave generator concepts which might impact the rf amplifier requirement for supercolliders; these are the FEL and the gyrotron. Because interaction in both these devices is with fast electromagnetic waves, no periodic structures or small gap cavities are required. The rf structure can be a smooth wall waveguide or a simple cavity with very large output coupling aperture. Operation in a higher order mode is feasible, and in general, transverse dimensions are much larger than in klystrons; thus, there is potential for developing very high peak power devices. In fact, short pulse (< 50 ns) experiments have demonstrated peak output power of ≈ 1 GW in gyrotron oscillators at S-band[8] and X-band[9] and in an FEL amplifier at 34.6 GHz.[10,11]

The FEL employs an undulator magnet with a periodic transverse magnetic field. It amplifies electromagnetic radiation with wavelength $\lambda = \beta_z \ell_w/(1-\beta_z)$ where ℓ_w is the undulator period and the normalized axial electron velocity is $\beta_z = v_z/c$. Usually the electron beam is streaming at relativistic velocities and $\lambda << \ell_w$. A recent FEL study at the Lawrence Livermore National Laboratory[10] employs a 3.5 MeV, 4 kA induction linear accelerator. A field emission cathode is used, and to improve electron beam quality, only a fraction of the diode current (850 A) is injected into the FEL interaction region. One gigawatt of output power has been obtained in 15 ns pulses at 34.6 GHz with a pulse repetition frequency of 0.5 Hz.[11] This experiment is typical of FEL's in that it uses an accelerator to drive the microwave generator rather than a conventional power supply and modulator. Consequently, the FEL mechanism is being considered for collider application in terms of a two-beam accelerator concept[12] rather than in terms of microwave tubes for driving a linac of conventional design. It should also be noted that high power FEL's have usually operated at short wavelength (λ < 1 cm).

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Although it may be worth consideration, we are unaware of any effort to develop high peak power FEL's at X-band.

Gyrotrons have a strong axial magnetic field and amplify electromagnetic waves at a frequency close to the electron cyclotron frequency. They generally operate at lower voltage than FEL's and are more likely to be compatible with conventional modulators. The gyrotron electron beam is usually annular with radius much larger than the Larmor radius, and is generated by a temperature limited magnetron injection gun. Thus, the gun configuration is very different from a klystron, and higher power may be attainable before reaching breakdown fields at the gun electrodes. An X-band gyrotron amplifier with pulse energy > 60 J is under development at the University of Maryland,[13] and the remainder of this paper will be devoted to describing the results of pertinent gyrotron experiments and design studies.

Phase Noise Measurements in a 50 kW Gyroklystron

The gyrotron amplifier configuration which promises to be most applicable to linacs is the gyroklystron which consists of several buncher cavities and an output cavity separated by drift spaces. In contrast to a conventional klystron, the electrons phase bunch in their cyclotron orbits rather than bunching in axial position. One important issue in assessing the suitability of gyroklystrons for high energy linacs is whether phase jitter is suitably small ($\lesssim 1^0$).

Phase jitter measurements have been carried out on a three-cavity, 5 GHz gyroklystron at the Naval Research Laboratory,[14] which produces 50 kW pulses with a 1-3 μs duration.[14] The gyroklystron cavities are rectangular and operate in the fundamental TE_{101} mode. A schematic of the gyroklystron and the phase detector circuit is shown in Fig. 1. A one watt, CW signal is coupled from the master oscillator into the first gyroklystron caviaty. A small sample of the master oscillator signal is drawn off before the gyroklystron and is sent to one side of the detector circuit which includes a sliding short for adjusting phase. After the sliding short, the master oscillator sample is fed to one arm of a balanced mixer. Another arm of the balanced mixer is fed with a sample of the gyroklystron output. The IF output port of the mixer yields a signal S given by

$$S(\phi) = AB \cos\phi + AB\,\delta \sin\phi \qquad (2)$$

where AB is the product of the electric field amplitudes of the two input signals, ϕ is the phase angle between the two signals, and δ is the phase jitter. By adjusting the sliding short to obtain S with $\phi = 0$ and then S with $\phi = \pi/2$, the phase jitter can be found as

$$\delta = \frac{S(\pi/2)}{S(0)} \,. \qquad (3)$$

Early experiments,[15] which made with no attempt to smooth the voltage and current pulses fed to the gyroklystron resulted in phase jitter of 20^0 during the pulse with a jitter frequency of about 6 MHz. This phase jitter was accompanied by a 1% ripple in the current at about the same frequency. The installation of a 1200 pf capacitor between the cathode and final anode of the gyroklystron reduced the current ripple to less than 0.3% and the phase jitter to 0.75%.[16]

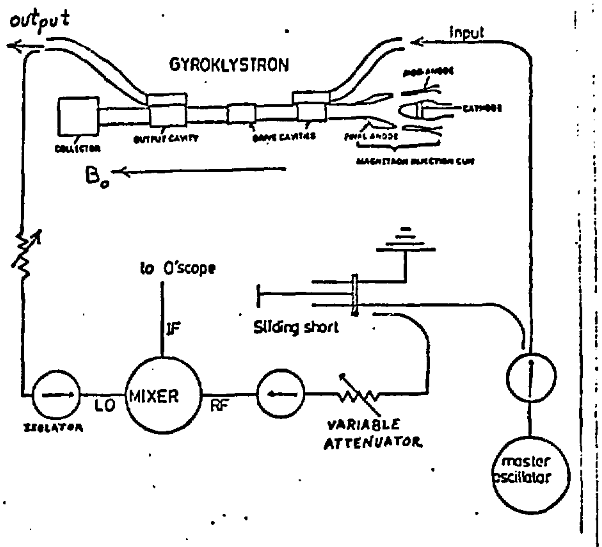

FIG. 1. Schematic of gyroklystron and phase detector circuit.

Pulse-to-pulse phase jitter was also measured because it is relevant to the ability of many gyroklystrons to start together in phase. This measurement is made by observing the mixer ouput (at a single point in time into the pulse) for many pulses. From the earliest experiments, the pulse to pulse phase jitter was measured as $< 0.25^0$.[15,16]

Phase jitter is subject to reduction by feedback circuitry. These measurements of phase jitter, $< 1^0$ in a gyroklystron without feedback stabilization, give good promise that higher power gyroklystrons can be operated with phase jitter sufficiently small for application to high energy linacs.

Gyroklystrons and Pulse Compressors for Application to Supercolliders

Development of an X-band gyroklystron with 30 MW, 2 μs pulses is underway at the University of Maryland; if successful, this development will represent an advance in pulse energy by two to three orders of magnitude together with a twofold increase in frequency when compared with the state-of-the-art 50 kW, C-band amplifier described in the preceding section. A similar leap in microwave source capability was made when conventional klystron amplifiers were developed for application to linacs.

To avoid excessive space charge effects, a 500 keV electron energy is chosen in the X-band gyroklystron. Furthermore, since only perpendicualr electron energy is converted to microwaves in gyrotrons, $v_\perp$ is chosen larger than $v_\parallel$; viz., $v_\perp/v_\parallel = 1.5$. Thus, $v_\perp = 0.72$ c and the larmor radius $r_L = 0.4$ cm; such a large value of r_L implies an annular electron beam which is too large to fit inside a gyroklystron based on the fundamental mode. Therefore, the TE^0_{011} mode is chosen for all the circular cross-section cavities of the gyroklystron. This mode, which is circularly symmetric, can interact effectively with all the electrons in the annular beam resulting in high efficiency when compared with non-symmetric modes. Spurious oscillation in lower order modes can be suppressed in the drift tubes, and if necessary in the cavities, by slotting the walls to prevent axial current flow. No axial wall currents accompany the TE_{011} mode.

The detailed design of the four-cavity TE^{o}_{011} gyroklystron is described in a companion paper in these proceedings.[17] The salient design parameters are summarized in Table I where they are compared with the parameters of the 150 MW, five-cavity, S-band klystron.[5]

Table I. Design parameters of a four-cavity TE^{o}_{01} gyroklystron.

	Gyroklystron	Klystron
Frequency	10 GHz	2.87 GHz
Electron Energy	500 kV	475 kV
Electron Beam Current,	160 A	621 A
Peak Output Power, P_p	33 MW	150 MW
Maximum E-Field at Electrodes	91 kV/cm	234 kV/cm
Pulse Duration	2 μs	1 μs
Efficiency	41%	51%
Gain (at saturation)	61.4 dB	59.3 dB

Note that as suggested previously, the parameter P_p/λ^2 can be larger in a gyroklystron than in a conventional klystron. Also, the maximum electric field at the gun electrodes is considerably smaller in the gyroklystron implying that larger pulse duration could be used before encountering breakdown.

A binary pulse compression circuit which uses the TE^{o}_{01} mode has recently been described.[18] By taking advantage of the unusually small wall losses which accompany the TE^{o}_{01} mode, the pulse compessor can be designed to operate with high efficiency. Taking the 33 MW, 2 μs output pulse from the gyroklystron parameters in Table I and passing it through a four-stage binary pulse compressor with assumed 90% efficiency results in a final peak power of 475 MW with a 120 ns pulse duration. These pulse parameters are close to those required for driving an X-band linac with E_a in the range 100-200 MV/m assuming one gyroklystron per accelerator feed.

Summary

There are good prospects for developing high gain, X-band microwave amplifiers with good phase stability, reasonable efficiency, and with pulse energy > 60 J as required for each feed port of a supercollider. While klystrons, lasertrons, and gyrotrons are all possible choices for the amplifier type, it appears that at X-band, the gyrotron may have some advanvtage both in the achievable peak power and in the pulse duration. However, this conclusion is based on gyrotron design calculations and awaits experimental confirmation. Finally, the development of efficient pulse compression circuitry using the TE^{o}_{01} mode appears to be of great importance in effectively exploiting the gyrotron amplifier for the supercollider application.

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