PROSPECTS FOR DEVELOPING MICROWAVE AMPLIFIERS TO DRIVE MULTI-TeV COLLIDERS

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Abstract

In multi-TeV linear colliders, overall accelerator length can be kept reasonable only if a high value of accelerating field is chosen, and this implies a relatively high value of rf frequency in order to avoid excessive dark current. We consider the feasibility of developing 30 GHz gyroklystron amplifiers. Amplifier output would be at the fourth harmonic of the electron cyclotron frequency to keep the magnetic field small (B_0 = 4.3 kG). Efficiency would be maximized both by a scheme of doubling the amplifier input frequency in two stages and by using depressed collectors. We estimate that output power in a single amplifier would be >80 MW with overall electronic efficiency ∼66%. With a high degree of pulse compression (32X), 1800 such amplifiers would drive a 3 TeV collider.

I. INTRODUCTION

The design study of future linear colliders which was carried out at the Snowmass Workshop in 1990 included consideration of a collider with final energy U_f = 3.0 TeV, and accelerating gradient E_a = 100 MV/m [1]. To avoid excessive dark current emission in the accelerator at this value of E_a, a relatively high value of rf frequency was chosen; i.e., 30 GHz. We note that a similar frequency has been chosen for the two-beam, CLIC accelerator design at CERN [2]. In this paper, we consider the alternative of developing individual 30 GHz amplifier tubes; larger efficiency may be realizable in individual microwave tubes than with a two-beam arrangement.

The advantage of using a high rf frequency is clear if the pulsed microwave energy from each amplifier can be made comparable to pulsed energy obtainable from lower frequency amplifiers. In Eq. (1), an expression is given for N_t, the number of microwave amplifiers required to drive a collider with given final energy U_f and accelerating gradient E_a; viz. [3]

$$N_t \approx 1.7 \times 10^7 \frac{U_f E_a \lambda^2}{P_p \tau_p \eta_c} \qquad (1)$$

where mks units are used, and $\lambda,\ p_p$, and τ_p are, respectively, the operating wavelength, the peak output power and the output pulse duration of a single microwave amplifier; η_c is the efficiency of any pulse comparison circuit that is used.

It should be noted that a new pulse compression scheme is being studied at SLAC [4] which, if successful, would keep η_c large even when there is a high degree of pulse compression. In line with the most optimistic projections of the SLAC study, we consider pulse compression by a factor $C_r = 32$ and a corresponding compression efficiency of $\eta_c = 80\%$; at 30 GHz, $C_r = 32$ implies that the amplifier output would have a pulse duration of τ_p = 0.7 μs. Then if one could achieve an amplifier output power of 80 MW, the number of amplifiers required to drive a 3 TeV collider with E_a = 100 MV/m, can be calculated from Eq. (1) as N_t = 1800.

In contrast, one can consider the case of a 3 GeV collider driven by 11.4 GHz klystrons with output power 50 MW and pulse duration 1.5μs. The acceptable value of E_a would then be limited to ∼50 MV/m, making the collider twice as long. Moreover, the number of amplifiers required would be N_t = 3600.

II. A PROPOSED 30 GHz, FOURTH-HARMONIC GYROKLYSTRON

When considering what type of amplifier to choose at 30 GHz, the gyroklystron stands out as a preferred choice. Gyroklystrons have been successfully operated with cavities resonant in high order modes, and with drift spaces which are not cut-off. In general, as gyroklystrons are scaled to higher frequency, their transverse dimensions can remain large by choosing resonant modes of higher order in the cavities, and by taking measures to stabilize the drift spaces against a larger number of potential instabilities. Thus, the power rating of gyroklystrons does not need to decrease as frequency is raised.

A 20 GHz gyroklystron has already been demonstrated with output power P_p = 32 MW, and τ_p = 0.8 μs [5]. The output cavity was driven at 10 GHz near the electron cyclotron frequency, ω_{ce}, and the output cavity operated at the second harmonic; efficiency was 28%. A more powerful gyroklystron with second harmonic output cavity and design values of $P_p \gtrsim$ 100 MW at 17.4 GHz is under construction; a co-axial circuit is being used to increase stability against spurious oscillations [6]. Efficiency as high as 42% has been calculated [7].

We now consider the feasibility of a 30 GHz gyroklystron with desirable parameters for application to driving a 3 TeV collider. It would be advantageous to operate the output cavity at the fourth harmonic of ω_{ce} so as to minimize the solenoidal magnetic field requirement. In its simplest embodiment, the gyroklystron circuit would be made up of three cavities, the input cavity operating at $\omega \approx \omega_{ce}$, the center cavity at $\omega \approx 2\omega_{ce}$, and the output cavity at $\omega \approx 4\omega_{ce}$; modes in the three cavities might be TE_{011}, TE_{021}, and TE_{041}. Efficiency which can be achieved with such a two-stage multiplication of frequency is much larger than efficiency in an amplifier which transitions from the fundamental frequency to the fourth harmonic in a single stage [8].

A recent calculation [8] of the maximum electronic efficiency which can be achieved in such a staged frequency quadrupling gyroklystron indicates that an electronic efficiency $\eta_e \approx 30\%$, is achievable for a gyroklystron electron beam with aspect ratio $v_\perp/v_\parallel = 1.5$ and parallel velocity spread $\Delta v_\parallel/v_\parallel < 6\%$. In the 500 kV electron gun built for the 17.1 GHz gyroklystron [6],

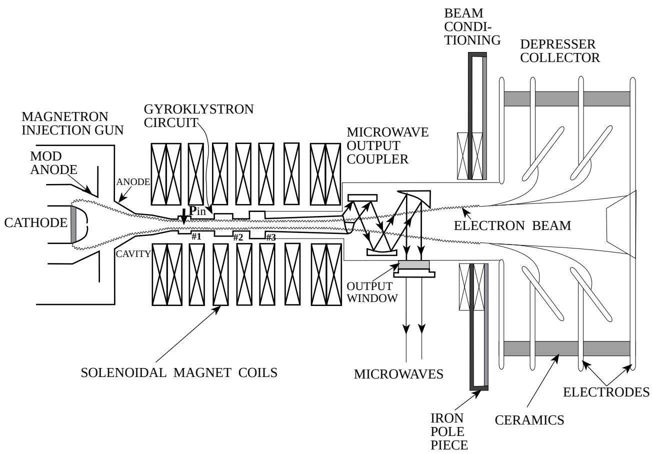

Figure 1. Schematic of a fourth-harmonic gyroklystron including depressed collector.

$\Delta v_{\|}/v_{\|} \lesssim 6\%$ is achievable for beam current $I_b \lesssim$ 600 A. Very preliminary attempts [7] to design a specific fourth harmonic gyroklystron circuit have produced calculated values of $\eta_e = 13\%$.

III. EFFICIENCY ENHANCEMENT BY USING A DEPRESSED COLLECTOR

To enhance efficiency over the single-pass values of η_e cited above, one can employ depressed collectors. A numerical study of depressed collectors for a gyroklystron with 30 MW output power has been carried out [9] with results summarized in Table I where η_c is the collective efficiency and $\eta_t = \eta_e/(1-\eta_c(1-\eta_e))$ is the total electronic efficiency. Note that even with only two electrodes in the depressed collector a single pass efficiency η_e near 30% results in a total electronic efficiency $\eta_t \sim$ 60%.

Figure 1 is a schematic of a three-cavity gyroklystron with a multi-electrode depressed collector. A three electrode magnetron injection gun is used so that dc power supplies can be employed in the collector circuits with the beam current controlled by applying voltage pulses to the mod anode. Also shown is a microwave output coupler of the Vlasov type which couples microwave energy out through a window mounted on the sidewall of the gyroklystron [10]; thus, the microwave energy does not enter the collector structure where it would constrain collector design. Finally, it will be noted that a beam conditioning section precedes the depressed collector; such a section provides magnetic fields which convert transverse energy to axial energy, and has been used to advantage in combination with gyrotron depressed collectors [11].

The operating parameters of a 30 GHz gyroklystron which might be achieved in the future are estimated to be those displayed in Table 2. Such performance would merit consideration in planning a 3 TeV collider.

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Table I. Efficiency of gyroklystrons with multiple stage depressed collectors.

Single-pass electronic efficiency	No. of collector electrodes					
	2		3		4	
η_e	η_c	η_t	η_c	η_t	η_c	η_t
10%	79%	35%	85%	43%	86%	44%
20%	76%	51%	82%	58%	84%	61%
30%	74%	62%	81%	69%	83%	72%

Table II. Estimated operating parameters that might be achieved in a 30 GHz gyroklystron.

e-beam energy	500 keV
e-beam current	600 A
η_e, single pass electronic efficiency	28%
P_p, microwave output power	84 MW
η_c, depressed collector efficiency	80% (3 electrodes)
η_t, total electronic efficiency	66%
τ_p, microwave pulse duration	0.7 μs
$f_{\rm in}$, input frequency	7.5 GHz
B_0, solenoidal magnetic field	4.3 kG
$f_{\rm out}$, output frequency	30 GHz