

A Review of Gyroklystrons and a Cost Estimate for a Gyroklystron-Driven Supercollider

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Abstract

Gyroklystrons avoid the small gap cavity structures which might cause breakdown problems in conventional klystrons. As a result it is believed gyroklystron performance will scale to higher power at higher frequency. Attainable peak power in a gyroklystron amplifier is estimated to be 105 MW at 17.14 GHz. The application of such amplifiers to driving a linear collider such as the TLC (1 TeV center of mass energy, 2.5 km length per linac) is shown to be optimized for an accelerator field length of 3 m, corresponding to a gyroklystron pulse length of 1.8 μ s (pulse compression by a factor of 16 is assumed). The number of gyroklystrons required per linac would be 833. The cost of the RF system for a gyroklystron-driven TLC is estimated to be \$0.65 billion.

Introduction

Gyroklystrons are among the RF amplifier options under consideration for driving linear supercolliders. They are expected to scale to higher peak power at higher frequencies than are conventional klystrons. The reason for this expectation may be appreciated by considering the simplified sketches in Fig. 1.

In the conventional klystron shown in Fig. 1(a), a streaming electron beam is velocity modulated by the RF signal in the narrow gap of a re-entrant input cavity. This modulation subsequently results in axial ballistic bunching of the electron density in a drift tube, and finally, the bunched electron beam passing through a second narrow gap constitutes an RF current which generates RF power in the re-entrant output cavity. Efficient RF power generation requires that the cavity gaps be small compared with the RF wavelength, and thus, it is not difficult to imagine that for a given pulse length, RF output power would be limited by breakdown in the output cavity gap. Indeed, in recent high peak power klystron experiments carried out jointly by SLAC and LLNL,¹ observations of pulse shortening indicate that output gap breakdown is occurring; at 11.4 GHz, when output power reached 80 MW the pulse duration was shortened to a few nanoseconds.

The gyroklystron configuration sketched in Fig. 1(b) may be contrasted with the conventional klystron configuration. In the gyroklystron, an annular beam of electrons gyrating in an externally applied magnetic field is energy modulated by the RF field in an input cavity. Subsequently, in a drift tube, the beam electrons ballistically bunch in phase in their cyclotron orbits. Finally, the phase bunched electrons emit coherent cyclotron radiation by coupling to the RF fields in an output cavity. The electrons in this type of an amplifier do not bunch in space, and no small gap in the output cavity is required. In fact, the electrons can even interact with a higher order mode of the output cavity whose resonant frequency is matched to the electron cyclotron frequency, and thus the cavity dimensions can be large compared to the RF wavelength. Thus, gyroklystron peak power will not be limited by breakdown in the RF output cavity. Instead, the power limitation will likely

be imposed by the features of the magnetron injection gun used to produce the spiralling electron beam. Magnetron injection gun scaling has been analyzed by W. Lawson² and he has demonstrated that peak power scaling with frequency will be as $P_p \sim \omega^{-1}$. This scaling may be considerably more favorable for going to higher frequencies, than the scaling of the power limit imposed by breakdown in conventional klystron cavities.

To date, experimental studies of gyroklystrons have been meager in number especially when compared with the abundance of research and development work on conventional klystrons. An early gyroklystron study at Varian Associates³ did produce a 50 kW of output power at 28 GW in the TE₀₂⁰ mode; however, efficiency was only 10%. This relatively low value of efficiency has subsequently been attributed⁴ to failure to take into account the effects of electron velocity spread in the gyroklystron design. Gyroklystron analysis techniques which account for velocity spread are now available,⁵ and have been used at NRL to design a 3-cavity, 5 GHz gyroklystron operating in the fundamental TE₀₁ mode. This C-band gyroklystron has operated with a linear gain of 36 dB and a saturated output power of 45 kW corresponding to 30% efficiency.⁶ In addition, the high frequency phase jitter of this gyroklystron has been reduced to $< 1^\circ$.⁷

The results of the 44 kW, C-band gyroklystron experiment are encouraging, but gyroklystrons have not yet been operated at the peak power levels that would be relevant for the supercollider application. However, studies of single-cavity gyrotron oscillators indicate that such power levels are achievable. In a recent oscillator study at NRL,⁸ 250 MW of output power was produced in a 40 ns long pulse at a frequency of 35 GHz. This performance exceeds by a large margin the performance demonstrated to date in the SLAC/LLNL study of conventional klystron circuits, and it indicates that gyroklystron performance will not be limited by breakdown in the output cavity.

Gyroklystron Designs Relevant to Supercolliders

The demonstration of gyroklystron amplifiers with parameters of interest in providing RF sources for linear supercolliders is being pursued at the University of Maryland.⁹ The most recent report on the status of University of Maryland program has been presented by W. Lawson at the Linac '88 Conference.¹⁰ A initial experiment in 1989 with a two-cavity circuit is expected to demonstrate gain of 27 dB and an output power of 26 MW at 10 GHz with a pulse duration of 1 μ s. Follow-on experiments will involve demonstration of higher gain in circuits with more than two cavities.

The design parameters of a planned four-cavity gyroklystron experiment at 10 GHz are listed in column A of Table 1. Beam power is 80 MW while predicted output power is 36 MW corresponding to efficiency of 45% which is achieved by stagger tuning of the penultimate cavity.¹¹ The predicted gain of 63 dB is larger than in a five cavity conventional klystron of comparable output power.¹ Note that the cathode emissivity and especially the peak electric field at the cathode are quite con-

servative. The realization of a 36 MW, high gain, X-band gyrokystron will constitute a very large step forward in gyrokystron capabilities, and will establish the relevance of this type of amplifier to large RF particle accelerators.

However, to make linear supercolliders affordable, gyrokystrons with ever higher peak output power, and operating at higher frequencies will likely be required. In this connection, it is of interest to consider the scaling of electron beam power in a magnetron injection gun with salient beam parameters,^{2,10} viz.,

$$P_b \sim r_g E_c V_0^2 \left[1 + \left(1 + \frac{eV_0}{mc^2} \right)^{-1} \right]. \quad (1)$$

The parameters r_g , E_c and V_0 are defined in Table I.

A magnetron injection gun for an X-band gyrokystron¹² has been designed with beam power of 400 MW, and its parameters are tabulated in column B of Table I. The higher power was primarily achieved by increasing the voltage from $V_0 = 500$ kV to $V_0 = 800$ kV and by doubling the value of the guiding center radius r_g . It was proposed that a TE₀₁ co-axial gyrokystron circuit be used in place of the TE₀₁ hollow cylindrical circuit to accommodate the larger electron beam without aggravating the problem of spurious modes. While the efficiency of this beam and circuit combination has not yet been analyzed, we estimate that it can be made close to the 45% value calculated for the 500 kV gyrokystron in column A; then, the output power of the 800 kV, co-axial gyrokystron in column B is estimated to be 180 MW.

The two gyrokystrons represented by the parameters in columns A and B are sketched in Fig. 2, where they may be compared in size. The co-axial center conductor for the design of column B would of course need to be supported at its end(s). It may be feasible to run an insulated support rod through the center of the cathode stalk and/or to attach the center conductor to the middle of the output window.

Finally in Table I, we present estimated parameters for an 800 kV gyrokystron operating at a frequency of 17.136 GHz. The parameters have been obtained from the 800 kV X-band design by scaling the guiding radius for the electron beam and the circuit radius with the wavelength while assuming that the field at the cathode can be kept constant. It is clear from Eq. (1) that such scaling implies that beam power will also scale as the wavelength; i.e. $P_b \sim \lambda$. Cathode emissivity scales² as $\lambda^{-1/3}$ to a value of 5.3 A/cm² which is readily achievable. The applied axial magnetic field increases to 1.3T which may imply the use of a superconducting solenoid with the gyrokystron. Again, assuming that efficiency will be 45%, we estimate the output power of the 17.136 GHz gyrokystron as 105 MW. As will be seen below, such a gyrokystron would be useful in linear supercolliders which are presently under consideration.

The Number of Gyrokystrons Needed to Drive TLC

The scaling of gyrokystron power linearly with wavelength ($P_b \sim \lambda$) represents a more gradual fall in power than is expected in other RF sources such as klystrons. This implies that as RF design frequency for a given accelerator becomes large a smaller number of gyrokystrons will be required to drive the accelerator, and capital costs are closely tied to the number of RF sources.

To make these thoughts more specific, we will consider the number of gyrokystrons to drive a future linear collider such as the TLC¹³ contemplated at SLAC. The TLC is to have a center of mass energy of 1 TeV and a length per 0.5 TeV accelerator

of $L_a = 2.5$ km. This corresponds to an accelerating gradient of $E = 200$ MV/m. We assume that a SLAC-like disk-loaded accelerating structure will be used but with a larger aperture radius than at present to minimize wakefield effects; preliminary TLC designs propose an aperture radius to wavelength ratio of $a_\lambda = 0.2$.

The number of RF tubes per accelerator is given by the equation

$$N_t = P_f L_a / (P_p 2^m L_f), \quad (2)$$

where P_f is peak power per feed, P_p is peak power per RF tube, m is the number of stages of binary pulse compression, L_a is the length of each accelerator (2.5 km for TLC), and L_f is a feed length.

We will assume that four stages of binary pulse compression¹⁴ are to be used so that $2^m = 16$. Power per RF tube will be specialized for gyrokystrons of the type indicated by columns B and C of Table I with $P_b \sim \lambda$ scaling so that

$$P_b = 6 \times 10^9 \lambda, \quad (3)$$

where P_p is in watts and λ is in meters.

Peak power per feed is given by

$$P_f = W_s v_g / n_s, \quad (4)$$

where W_s is stored energy for unit length, v_g is the group velocity and n_s is the structure efficiency. The quantities in Eq. (4) may be evaluated using the accelerator design equations of Farkas.¹⁵

Then group velocity is given by

$$\frac{v_g}{c} = \beta_g = \exp\left\{3.1 - \frac{2.4}{\sqrt{a_\lambda}} - 0.9a_\lambda\right\} = .0866. \quad (5)$$

To calculate W_s , one first needs to know the value of elastance per unit length, which is given by

$$s = v_g \lambda^{-2} [41.3 a_\lambda^{-3.836}] = 5.15 \times 10^{11} \lambda^{-2}, \quad (6)$$

where s is in ohms/m² and λ is in meters. Stored energy per unit length may then be approximated by

$$W_s = E_a^2 / s = 7.77 \times 10^5 \lambda^2, \quad (7)$$

where W_s is in watts and λ is in meters.

The structure efficiency, n_s , depends on the ratio of fill time, T_f , to attenuation time, T_0

$$T_f = L_f / v_g = 3.85 \times 10^{-8} L_f, \quad (8)$$

where T_f is in seconds and L_f is in meters.

$$T_0 = \lambda^{3/2} [45.5(1 + 1.25\beta_g^{3/2}) - 3\beta_g] \times 10^{-6} = 4.67 \times 10^{-5} \lambda^{3/2}, \quad (9)$$

where T_0 is in seconds and λ is in meters. Combining equations (7) and (8) we find the structure parameter

$$\tau = T_f / T_0 = 8.24 \times 10^{-4} L_f \lambda^{-3/2}, \quad (10)$$

where τ is in seconds, L_f is in meters, and λ is in meters. The structure efficiency may then be evaluated from the expression

$$n_s = (1 - e^{-2\tau}) / 2\tau. \quad (11)$$

For $\tau \ll 1$ (i.e., long wavelength or short feed length), $n_s \approx 1$, while for $\tau \gg 1$, $n_s \approx 1/2\tau$.

Then combining equations (2), (3), (4), (6), (9) and (10), one obtains the following expression for the number of gyrokystrons required per linac

$$N_t = 5.26 \times 10^4 \lambda L_f^{-1} (2\tau/1 - e^{-2\tau}) \quad (12)$$

where τ is given by Eq. (10), and where L_f and λ are both in meters.

For $\tau \ll 1$, Eq.(1) reduces to

$$N_t \approx 5.26 \times 10^4 \lambda L_f^{-1}, \quad (13)$$

so that in this long wavelength limit, the number of gyrokystrons will decrease as frequency is made large provided that L_f is fixed. This is a consequence of the accelerator cross section area and stored energy falling as λ^2 while the power per gyrokystron only falls as λ .

In the short wavelength limit, wall loss effects will dominate. Thus for $\tau \gg 1$, Eq. (11) becomes

$$N_t \approx 87\lambda^{-1/2}, \quad (14)$$

and the number of tubes rises as frequency increases. Thus, for a fixed feed length one expects an optimum value of RF wavelength where the number of required gyrokystrons will be minimum.

In Fig. 3, we have plotted N_t as a function of λ for various fixed values of L_f . The number of tubes will of course be diminished as L_f is increased, but the required gyrokystron pulse length ($T_p = 2^m T_f$) will increase. For $L_f = 3$ m, we calculate from Eq. (7) that $T_f = 115$ ns and $T_p = 1.85$ μ s; this is probably about as long a pulse length as can be accommodated if breakdown problems in the gyrokystron electron gun are to be avoided.

With $L_f = 3$ m, the minimum value of N_t occurs near $\lambda = 1.75$ cm (i.e., 17.14 GHz) where $N_t = 744$. The number of feeds per linac is close to this value (viz., $L_a/L_f = 833$) so that one gyrokystron per feed would be a reasonable design estimate, and would allow for some loss in the pulse compression circuit; the gyrokystron would be of the type listed in Table I, column C.

Estimated Capital Cost for the RF System of a Gyrokystron Driven TLC

To roughly estimate the capital costs of the gyrokystrons and their associated modulators and pulse compression circuits that would be required for both accelerators in TLC, we use the following model

$$\text{Capital Cost} = 2N_t[C_{mod} + C_t + C_{mag}] + N_t[C_{st}m + C_{dl}L_{dl}] \quad (15)$$

where C_{mod} is the cost of a unit modulator, C_t is the cost of a gyrokystron tube, C_{mag} is the cost of a gyrokystron magnet, C_{st} is the cost of components per stage of binary pulse compression, C_{dl} is the cost of delay line per unit length, and L_{dl} is the length of delay line.

Based on experience with manufacturing SLAC klystrons,¹⁶ we estimate $C_{mod} = \$150,000$ and $C_t = \$150,000$. The superconducting magnet required by the 17.14 GHz gyrokystrons together with refrigeration units will have an approximate per unit cost of $C_{mag} = \$50,000$. The cost of binary pulse compression components is estimated¹⁷ as $C_{st} = \$3,000$ per stage, and the cost of delay line $C_{dl} = \$140/m$. The length of delay line for each binary pulse compression unit is

$$L_{dl} = (2^m - 1)cT_f = 520m. \quad (16)$$

Then, the capital costs for the RF system of the TLC may be calculated from Eq. (12) using $N_t = 833$. The capital cost is \$0.65 billion, of which 11% is contributed by the cost of the pulse compression circuit.

It remains to choose a pulse repetition frequency that is consistent with a reasonable value of average power consumption. One would then need to complete the collider design (e.g., choose the number of particles per bunch and the number of bunches per pulse, etc.) to yield the required luminosity.

Summary

Gyrokystron amplifiers with parameters which are relevant to driving linear supercolliders are under development at the University of Maryland. It is estimated that gyrokystrons could be developed with peak output power in watts given by $P_p = 6 \times 10^9 \lambda$ where λ is the wavelength in meters; also P_p might be further enhanced by as much as a factor of 16 through use of binary pulse compression circuitry. The scaling of P_p linearly with wavelength represents a slower fall-off in power with increasing frequency than is expected with other types of RF sources.

When one plots the number of gyrokystron tubes required for a given accelerator, N_t , as a function of wavelength with feed length fixed, the curve of N_t vs. λ has a minimum. For the parameter of the TLC and for a feedlength of $L_f = 3$ m, the minimum in N_t falls near $\lambda = 1.75$ cm (17.14 GHz). Then one can propose a TLC design at 17.14 GHz with one gyrokystron per feed or 833 gyrokystrons per accelerator. The cost of the RF system for such a gyrokystron-driven TLC is estimated to be \$0.65 billion.

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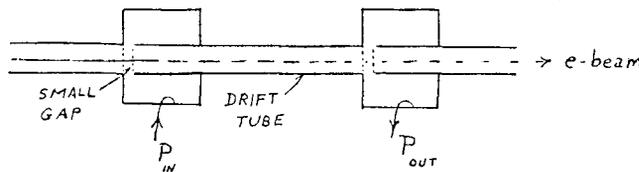
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TABLE I.
Gyroklystron Design Parameters

	A	B	C
Frequency, ω	10 GHz	10 GHz	17.14 GHz
Voltage, V_0	500 kV	800 kV	800 kV
Current	160 A	500 A	290 A
Cathode Emissivity	5.6 A/cm ²	4.6 A/cm ²	5.3 A/cm ²
Cathode Electric Field, E_c	90 kV/cm	80 kV/cm	80 kV/cm
Velocity Ratio, v_{\perp}/v_z	1.5	1.5	1.5
Final Guiding Center Radius, r_g	0.8 cm	1.6 cm	0.9 cm
Drift Tube Radius	1.5 cm	2.24 cm	1.31 cm
Mode	TE ₀₁ ^o	TE ₀₁ ^o	TE ₀₁ ^o
Gain	63 dB	—	—
Efficiency	45%	—	—
Peak Output Power, P_p	36 MW	180 MW	105 MW
Applied Axial Magnetic Field	0.565 T	0.73 T	1.3 T

(a) KLYSTRON



(b) GYROKLYSTRON

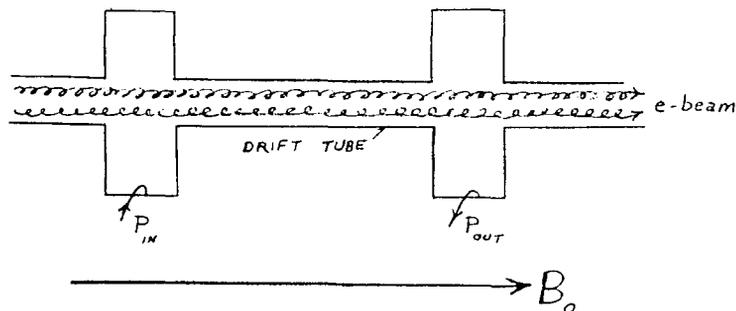


Fig. 1. Simplified schematics of (a) a conventional klystron and (b) a gyroklystron. For simplicity, both devices are shown with two cavities separated by a drift space. In general, higher gain may be realized by utilizing a number of intermediate cavities and drift spaces.

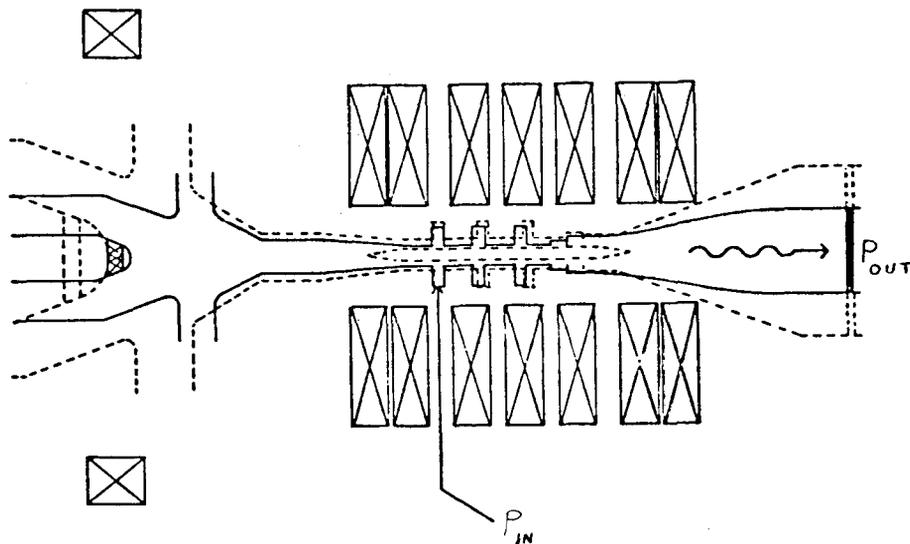


Fig. 2. Comparison of the relative dimensions of a 500 kV, 36 kW, TE_{01}° gyrokystron (solid lines), and an 800 kV, 180 MW, TE_{01}° gyrokystron (dashed lines).

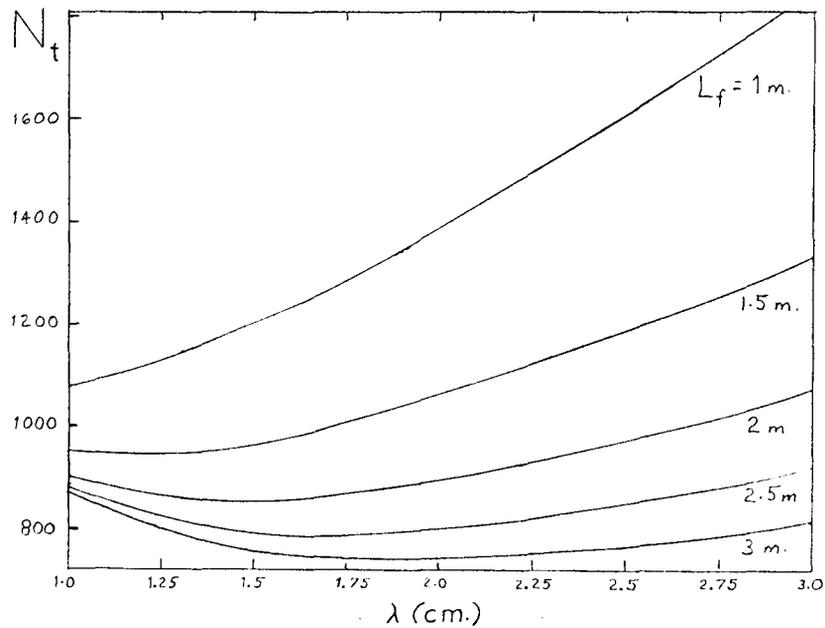


Fig. 3. Number of gyrokystrons per linac vs. wavelength. Each linac will accelerate particles to 0.5 TeV in a 2.5 km length. L_f is feed length.)