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Abstract

In order that it may be built within a reasonable length and with reasonable ac power consumption, a 5 TeV linear collider must employ an accelerating gradient and rf frequency which are both higher than for present 1 TeV collider designs. The required rf power per meter, which will also be higher than for 1 TeV designs, can be provided either by relatively conventional rf technology or by a two-beam scheme such as that proposed for CLIC. In this paper the first alternative, a 30 GHz rf system employing microwave tube power sources together with rf pulse compression, is described which produces an accelerating gradient on the order of 200 MV per meter. Limitations on the peak power that can be obtained from conventional klystrons as a function of frequency are discussed; it is found that such klystrons are only marginally adequate as a power source at 30 GHz. Several alternative rf sources, such as multiple-beam klystrons, sheet-beam klystrons, gyroklystrons and annular-beam ubitrons are described which are capable of providing the required power, after pulse compression, of about 600 MW per meter.

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RF SYSTEM FOR A 30 GHz, 5 TEV LINEAR COLLIDER BASED ON CONVENTINONAL TECHNOLOGY[1]

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Abstract

In order that it may be built within a reasonable length and with reasonable ac power consumption, a 5 TeV linear collider must employ an accelerating gradient and rf frequency which are both higher than for present 1 TeV collider designs. The required peak rf power per meter, which will also be higher than for 1 TeV designs, can be provided either by relatively conventional rf technology or by a two-beam scheme such as that proposed for CLIC. In this paper the first alternative, a 30 GHz rf system employing microwave tube power sources together with rf pulse compression, is described which produces an accelerating gradient on the order of 200 MV per meter. Limitations on the peak power that can be obtained from conventional klystrons as a function of frequency are discussed; it is found that such klystrons are only marginally adequate as a power source at 30 GHz. Several alternative rf sources, such as multiple-beam klystrons, sheet-beam klystrons, gyroklystrons and annular-beam ubitrons are described which are capable of providing the required power, after pulse compression, of about 600 MW per meter.

1. INTRODUCTION

Initial parameter sets [1],[2] have been developed for a linear collider with a center-of-mass energy of 5 TeV, a luminosity on the order of $1 \times 10^{35}/\mathrm{cm}^2/\mathrm{sec}$, and an operating frequency in the 30-34 GHz range. To keep the length of the collider linac within reasonable bounds (on the order of 30 km), the operating gradient must be about 200 MV/m. Several potential problems immediately come to mind. First, can a gradient of this order be substained without rf breakdown, and even below the breakdown threshold, will field emission lead to unacceptable rf processing time or possibly to arcing, gas bursts and surface degredation during operation? Concerning the breakdown threshold, the results of Loew and Wang [3] extrapolated from X-band to 30 GHz indicate a breakdown surface field on the order of 1100 MV/m (corresponding approximately to an accelerating gradient of 450 MV/m) for pulses two or three microseconds in length. For pulse lengths on the order of 100 ns, as contemplated for a 30 GHz collider, the breakdown threshold should be considerably higher. Problems due to field emission tend to escalate above the dark current capture threshold gradient, which scales linearly with frequency. Experience with accelerating structures at S-band and X-band indicates that, using appropriate machining, cleaning and vacuum techniques, the structures can process and operate with satisfactory levels of field emission at gradients of at least 1-1/2 times the dark current capture gradient, or 240 MV/m at 30 GHz.

Before starting on a detailed design of a 5 TeV, 30 GHz linac operating at a loaded gradient of 200 MV/m, we need to ask whether a machine with these parameters can operate at a reasonable repetition rate with a reasonable ac wall plug power. The ac power for a machine with a gradient G, pulse length T_p, active length L_A, repetition rate f_r and rf system efficiency η varies approximately as $P_{ac} \sim f_r G^2 \lambda^2 T_p L_A/\eta$. Assuming that the pulse length varies in proportion to the structure filling time ($\sim\lambda^{3/2}$), and that the gradient is scaled as $G \sim \omega_{rf}$, the ac power then scales as $P_{ac} \sim f_r E_{c.m.} \lambda^{3/2}/\eta$. In scaling from the 11.4 GHz NLC design at 1 TeV to a 5 TeV collider at 30 GHz, the unloaded gradient will increase from 85 MV/m to 225 MV/m if $G \sim \omega$ scaling is followed. The factor $\lambda^{3/2}$ decrease the ac power by a factor of 4.3, almost balancing the five-fold increase in energy. Thus at a repetition rate of 120 Hz and a scaled pulse length of 60 ns, the ac power would remain nearly constant. In the design to follow, the pulse length will actually be about twice this, making it necessary to reduce the repetition rate to 60 Hz.

The peak power per meter required to drive the accelerating structure scales approximately as $P_m \sim G^2 \lambda^{1/2}$. For $G \sim \omega$ scaling, this becomes $P_m \sim \omega^{3/2}$. The NLC structure requires 145 MW/m for an unloaded gradient of 85 MV/m. This scales to 615 MW/m for a gradient of 225 MV/m at 30 GHz. A third question is, are rf sources available (or possible) which, together with a reasonable rf pulse compression system, can supply this peak power with a reasonable spacing between sources? The remainder of this paper will be devoted to answering this question.

2. BASIC RF-RELATED PARAMETERS

Table 1 gives basic rf parameters for a 30 GHz, 5 TeV collider for two accelerating structure designs.

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Table 1
RF Parameters for two Structure Designs

	Str. A	Str. B
Group Velocity/c	.067	.075
Structure Length (m)	0.70	0.75
Filling time T_F(ns)	35	33
Q	3500	4590
$T_0 = 2Q/\omega$ (ns)	37	49
$\tau = T_F/T_0$	0.95	0.68
Shunt Impedance(MΩ/m)	87.5	125
Unloaded Gradient (MV/m)	228	232
Loaded Gradient (MV/m)	200	200
Peak Power/meter (MW/m)	700	580
Power per Structure (MW)	490	435
Power per Klystron (MW)	74	66
Pulse Length at Str. (ns)	140	138
Pulse length at Kly. (μs)	1.12	1.10
AC Power (MW)	340	280

Structure A, having a shunt impedance of 87.5 MΩ/m, is a design developed[2] by the CLIC group at CERN. Dipole-mode damping is achieved by heavy coupling to external loads. Structure B is scaled from the current design for the NLC damped detuned structure having a shunt impedance of 95 MΩ/m at 11.424 GHz (group velocity = 0.05c). Scaling this to 30 GHz, opening up the iris to make $v_g/c = 0.075$ (to give lower wakefields and allow a longer structure length), and derating the shunt impedance r by –8% (5% in Q and 3% in r/Q) to allow for possible additional damping, results in a shunt impedance of about 125 MΩ/m. The beam loading current is based on a train of 200 bunches spaced 0.5 ns (15 λ) apart, each with a charge of 3×10^9 electrons. Including a 5% overhead allowance for feedback, etc., and assuming two 10 GeV injectors, the active length of both main linacs is 26.15 km. The pulse length includes a 5 ns rise time allowance. In calculating the ac power, an rf system efficiency of 45% is assumed: klystron, 60%; modulation efficiency (assuming a gridded tube), 91%; pulse compression efficiency, 82.5%.

At this gradient and pulse length, there is potentially serious problem with pulse heating at the copper surface, estimated be about 150^0C. The yield strength in copper is exceeded at a pulse temperature rise on the order of 40^0C [4]. However, the extent to which this surface damage might degrade the rf surface resistance is not clear; an experiment is underway at SLAC to measure the effects of pulse heating with a temperature rise of several hundred degrees on a demountable surface in an X-band cavity [5].

Finally, it would highly desireable to reduce the ac power by increasing the rf system efficiency above 45%. A reasonable goal might be: klystron, 65%; klystron modulation, 95%; pulse compression, 85%; system efficiency 52.5%. This would reduce the ac power by 15%.

3. RF PULSE COMPRESSION

The use of rf pulse compression to enhance the peak power output from the rf source becomes more important as the rf frequency increases and the power output capability of microwaves tubes tends to decrease. Several pulse compression schemes have the capability in principle of providing a peak power enhancement of 6.6, as assumed here, with reasonable efficiency. Current efforts at SLAC are being directed toward a so-called Delay Line Distribution System (DLDS) scheme in which the power from eight klystrons is combined to feed four groups of accelerating sections, each for a time equal to one-fourth of the klystron pulse length. In this scheme, power is directed to accelerating sections upstream (toward the gun), and the beam return time serves to reduce the delay line length by a factor of two. Applied to the present 30 GHz parameters, the klystron pulse length would be 4 × 140 ns = 560 ns, and there would by 30 m of delay line per meter of accelerating structure (compared to 9m/meter for the NLC design).

An alternatively possibility is a BPC (Binary Pulse Compression) system using loaded delay lines consisting of a series of 5–10 high Q energy storage cavities. Such a system having a compression ratio of 8 and a power gain of 6.6 (82.5% efficiency) is assumed for the parameters in Table 1. Although possible in concept, design details for such a system remain to be worked out.

4. RF POWER GENERATION AT 30 GHz

There are two basic limitations on the power that can be generated by a conventional round-beam klystron. First, it is well known that the electronic efficiency of a klystron depends on the microperveance, defined as $K_\mu = (I_b/V_b^{3/2}) \times 10^6$. An expression that fits recent simulations at SLAC is: $\eta = 0.75 - 0.17K_\eta$. To achieve an efficiency of at least 65%, the microperveance must be less than about 0.6. The output power at a beam voltage of 500 kV would than be less than about 68 MW. From Table 1, this marginally meets the klystron power requirement for the two cases shown.

A second limitation on klystron power is related to the area of the electron beam, which does depend on wavelength. To achieve good coupling to the longitudinal rf fields in the output gap, the radius of the beam should not be larger than about λ/8. If the beam radius exceed this, then electrons on the beam axis and electrons at the edge of the beam will see a substantially different rf gap voltage, and efficiency will suffer. Next, the beam area at the cathode can be larger than the beam area in the drift region by a factor A_c, the area convergence ratio. This ratio is limited by aberrations in the gun optics, transverse emittance, alignment tolerances, etc. A good measure of these effects is the convergence half-angle, which is related to the f-ratio of conventional optics. In practice, it is found that the convergence half-angle is limited to about 40^0, corresponding roughly to f 0.6. Because of the dynamics of space-charge-limited electron flow in the gun region, the gun focal length and hence the area convergence ratio depends on the perveance. By plotting A_c vs K_μ for a variety of gun designs with a convergence half angles of 35^0–40^0, the points can be crudely fit (within a factor of two or so) by [6] $A_c \approx 150/K^2_\mu$. A further limitation is the acceptable cathode loading current per square centimeter, I_A. Putting these factors together, the output power is

$$P_k \approx \eta V_b I_A A_c \pi(\lambda/8)^2 . \qquad (1)$$

If $A_c(K_\mu)$ as specified above is inserted in this and the result equated to $P_k = \eta K V_b^{5/2}$, an expression is obtained for the maximum allowable perveance:

$$K_\mu = 194 I_A^{1/3} \lambda^{2/3} / V_b^{1/2} . \qquad (2)$$

Taking $I_A = 10$ A/cm^2, $\lambda = 1.0$ cm and $V_b = 560$ kV, then $K_\mu(\max) = 0.59$ with a corresponding efficiency of 65% and output power of 68 MW. By coincidence, this is just the efficiency and output power specified above. At shorter wavelengths the perveance would have to be lower and the output power less (although the efficiency would be somewhat higher).

The bottom line is that it should be marginally possible to build a klystron at 30 GHz which has good efficiency (65%) and an output power or the order of 65 MW. To obtain this or higher power from a more coservative power source, there are several possibilities. For example, three or four lower perveance beams can be packaged together in the same vacuum envelope. Such a multibeam klystron having common rf cavities but separate PPM-focused beams has indeed been proposed [7].Klystrons using a sheet beam, which is essentially equivalent to many round beams in parallel, are capable (in simulations) of producing 150 MW at 34 GHz with good efficiency [8]. It is well known that gyroklystrons are also capable of producing high power at high frequency. At the University of Maryland, a coaxial-circuit gyroklystron frequency-doubled from 17 to 34 GHz has been designed which produces an output power of 150 MW at a simulated efficiency of 42% [9]. A single-stage depressed collector can increase the efficiency to 56%.

Another annular-beam device capable of delivering high power output at high frequencies is the Ubitron (FEL) proposed by McDermott et. al. [10]. Using a TE_{01}-mode coaxial cavity and a PPM wiggler, it produces a simulated output power of 250 MW at 11.4 GHz with an efficiency of 50%. It should still be capable of producing a high output power when scaled to 34 GHz.

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