HIGH GRADIENT SUPERCONDUCTING RF*

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All currently proposed methods of building a TeV linear collider at an affordable cost entail significant technological challenges. The use of superconducting accelerating cavities reduces the technological challenges to two parameters: the accelerating gradient and the Q_0. Pulsing the RF at about 30 Hz with a duty cycle of around 0.01 relaxes the requirement on Q_0, and makes Q_0 values presently achieved at lower gradients ($\sim 3 \cdot 10^9$) acceptable [1]. All other technical challenges are equal to or less difficult than those of the SLC. One key reason for the attractiveness of RF superconductivity for use in colliding linacs is the high Q_0, which permits the cavity to be filled with RF energy slowly. This keeps the RF sources from being at their peak power limit. If the sources were peak power limited, a larger number of sources and modulators would be required to obtain the same average power, thereby adding to the cost. A second key advantage of RF superconductivity is the high achievable ratio of fundamental Q_0 to higher-order-mode Q. This property permits many bunches to be passed through the accelerator during each RF pulse without encountering cumulative wakefield build-up, without dissipation of excessive power between beam bunches, without dumping excessive stored RF energy due to a high RF pulse rate, and without having wrong bunches collide near the interaction point. By using SLC values as practical limits for certain parameters, optimization of the accelerator design becomes straightforward. Details of this optimization are presented.

Introduction

Only two types of high energy physics accelerators are being widely considered for future construction. One is a circular proton-proton (p-p) collider with center-of-mass energy between 15 TeV and 40 TeV, such as the proposed Superconducting Super Collider (SSC) and Large Hadron Collider (LHC). p-p colliders have the advantages that the technology for building them exists, and that the high rest mass of the protons permits high energy to be achieved in circular accelerators without encountering intolerable levels of synchrotron radiation. p-p colliders have the disadvantage that protons comprise three quarks, making the identity and momentum of the initial state of an interaction between two quarks unknown except on a statistical basis. Lack of knowledge of the initial state makes identification of specific reaction channels more difficult, particularly if these channels are not predicted by theory.

e^+e^- linear colliders are the second type of high energy physics machine under widespread consideration for future construction. Such machines have the advantage that the initial state of the interaction is reasonably well known (some uncertainty is introduced by beamstrahlung), but have the disadvantage that no technology for constructing such a machine at an affordable cost exists. The following section discusses the technologies which are receiving attention for this application.

Possible Technologies for e^+e^- Linear Colliders

Normal conducting (copper) structures are under consideration. At S-band (the SLC frequency) and lower frequencies, the costs of building and operating a TeV collider are prohibitive: if a gradient below 5 MV/m is chosen, the structure costs are excessive; if a gradient above 5 MV/m is chosen, the costs of the klystrons and their modulators, as well as of the stored RF energy dumped at the end of each pulse, are excessive. Accordingly, frequencies well above S-band are under consideration. Again, low gradients are excluded because they imply intolerable structure costs. The selection of high frequencies and high gradients leads to two other problems: transverse wakefields scale as the fourth power of the frequency (for a fixed length bunch), and suitable sources capable of producing high peak power at high frequencies don't exist. The problem of the fourth power scaling of the wakefields is being attacked by using a head-to-tail energy spread to obtain Landau damping, and by trying to devise new accelerating structures with intrinsically lower transverse wakefields. The use of Landau damping leads to two additional problems: one is that the structure dimension, alignment, and jitter tolerances are extremely tight, and the other is that achromatic final focus designs don't exist. Research and development work is required to determine whether or not the required tolerances can be achieved. The final focus problem can be attacked either by removing the momentum spread before the final focus section, or by developing a final focus using lenses having much shorter focal lengths than presently available. Removal of the momentum spread poses the questions of whether or not this can be achieved to an adequate degree and of whether or not the beam remains intact in the region where the momentum spread has been removed. Development of much shorter focal lengths requires additional research.

Several possible methods of achieving high peak power at high frequencies are the subject of research and development work at many institutions. Lasertrons offer the potential of high efficiency, but pose the problem that RF power is generated in their DC gap. Higher voltage klystrons are being explored, as are gyroklystrons. The use of very large numbers of small klystrons is being explored. Sheet beam klystrons reduce space charge effects, but pose the problem of internal stripline modes. Non-concentric parallel beam schemes are being explored using either induction linacs or superconducting cavities as accelerators of the drive beam, and transfer cavities or free electron lasers as the RF generating devices. Further development is required to show that induction linacs and superconducting cavities are suitable for transporting the high current bunched beams required. Free electron lasers pose the problem of phase control. Transfer cavities pose the problem of transverse impedance. RF compression schemes, which reduce the peak power generation requirements, pose questions of pulse rise time, capital cost, and RF attenuation. High modulator costs are being attacked by considering magnetic pulse compression; attainment of adequately square pulses is the issue in this case.

Accelerators using two concentric beams raise the questions of whether the drive beam can be made to have adequate azimuthal uniformity not to cause excessive transverse kicks, and of whether a compromise in the driven beam hole diameter can be found which provides an adequate transformer ratio without creating an excessive transverse impedance.

Plasma accelerators using either beat waves or bunch pairs are being investigated. Attainment of adequate phase and amplitude control, and of adequate gradient uniformity over the driven bunch length, are major questions. In the case of bunch pairs, adequate alignment of the first and second bunches, to avoid transverse effects, is an additional question.

Switched power linacs require the development of suitable switches. Use of small beam holes to obtain a high transformer ratio implies a high transverse impedance. Use of a large beam hole requires high efficiency recovery of the pulse energy in order to avoid intolerable operating costs.

Fully superconducting S-band linacs, operating in a pulsed RF mode, reduce the questions to be answered to a single one: can gradients above 30 MV/m be achieved on a reliable basis? In order to answer this question affirmatively, field emission needs to be further suppressed and thermal-magnetic breakdown caused by localized hot spots needs to be further suppressed. A proof-of-principle that there are no fundamental obstacles to achieving 30 MV/m exists: an accelerating gradient of 31 MV/m in a single cell S-band superconducting cavity has been achieved [2].

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Salient Features of the Pulsed, All-Superconducting Solution

Use of an S-band structure results in moderate wakefields which would be equal to or lower than those encountered in the SLC.

By using pulsed RF with a 1% duty cycle, about a 20 Hz RF repetition rate, about 100 beam bunches per RF pulse, and a bunch-to-bunch spacing of 1.5 km, the need for an extraordinarily high Q (which would be necessary if the RF were operated CW) is eliminated.

The gradient is $\geq$ 30 MV/m at a $Q_0 \geq 3 \cdot 10^9$.

None of the other requirements of the machine is more restrictive than the SLC.

The required gradient is the single parameter exceeding the present state-of-the-art. As mentioned in the preceding section, a proof-of-principle exists that there are no fundamental obstacles to achieving such a gradient.

Why is the Pulsed Superconducting Approach Attractive Relative to Copper Structures at the Same Frequency?

There are two basic reasons that the S-band superconducting approach is attractive relative to S-band copper structures. The first of these reasons results from the fact that the Q_0 of the superconducting cavity is $\geq 3 \cdot 10^9$. The high Q_0 means that the RF energy stored in the structure does not dissipate rapidly. This, in turn, means that the RF energy does not need to be supplied in a short time in order to avoid being dissipated. High peak power sources are therefore not required in order to supply this energy; such sources represent a technological limit, requiring a large number of them at a high cost. Since the stored energy required to achieve a given gradient scales as the frequency squared, avoidance of peak power limitations permits a relatively low frequency (S-band) to be used. Use of a low frequency (S-band) avoids extreme problems with transverse wakefields, which scale as the fourth power of the frequency.

The second reason that use of pulsed superconducting cavities is attractive is that, in superconducting cavities, present designs permit higher order modes to be damped at 10^5 times the rate at which the fundamental is absorbed by the cavity walls. In copper cavities, due to the much lower Q_0, gaining even a factor of 10 in the damping of the higher order modes requires a large coupling probe in each cell; such probes cause considerable enhancement of the local electric and magnetic fields, and disturb the cylindrical symmetry of the field pattern. In the superconducting case, the high ratio between the damping rates for higher order modes and for the fundamental mode means that there exist bunch trains with bunch spacings such that the higher order mode (wakefield) damping between bunches is very thorough, and the cell wall fundamental power absorption between bunch passages is very small. Thus, many bunches can be accelerated during one RF pulse without encountering cumulative wakefield problems. A low RF pulse rate at a low duty cycle can be used. The average rate at which stored energy is dumped is thus low, because it is dumped once at the end of each RF pulse. Pulsing of the RF is therefore feasible in the superconducting case, and requirements on Q_0 are greatly relaxed. In the absence of pulsing, the Q_0 required to obtain a fixed value of dissipation per unit length would scale as the square of the gradient.

As just mentioned, the concept of duty cycle modulated RF in normal conducting linacs (with several beam bunches accelerated during a single RF pulse) does not result in an appreciable gain, as the stored RF energy is typically absorbed in a microsecond at S-band so that RF pulses longer than a microsecond do not save appreciable power. If successive bunches are passed through the linac with one microsecond spacing or less, the cumulative wakes of previous bunches will increase the effective emittance of the successive bunches. The transverse wake potential 2 mm after the passage of a delta-function bunch is only 0.6 times the peak potential 60 cm after the passage of this bunch [3]. Since the peak value of this potential decreases with time only due to damping of the modes responsible, and since the damping time is of the order of a microsecond, proposals in which 12 bunches are passed through the cavity in the order of a microsecond (83 ns spacing) have the risk that the wakefields of the succeeding bunches will add coherently and do considerable damage to the bunches near the end of the train. Since one bunch in the SLC requires extreme care and precision to keep its head from doing unacceptable damage to its tail, the case of 12 bunches represents a much more severe problem since the growth rate for the last bunch can be as much as 19 times the growth rate for the first. One may ask whether the interference can be chosen to be destructive rather than constructive; this is quite difficult, since the 12 bunches in the train have no predetermined betatron phase shift between them, and a situation which provides destructive interference for one phase shift may provide constructive interference for another. In addition, fluctuations in the deflecting mode frequencies due to dimensional tolerances, the fact that the wake potential changes appreciably over the length of a typical bunch, and the fact that the spacing between successive bunches is constrained to be an integral number of fundamental wavelengths make the problem even more difficult.

Optimization Procedure

The optimization procedures used in determining parameters of a pulsed superconducting TeV linac are as follow. Quantities taken as given are the center-of-mass energy at 2 TeV, the luminosity at 10^{33} $cm^{-2}sec^{-1}$, and the fractional energy spread at the collision point of $\sigma_{E^*}/E^* \leq 0.1$.

Certain quantities are taken to be at practical technological limits, even though pushing these quantities further in the same direction would be beneficial. These values are chosen to be similar to those of the SLC on the premise that, if it were easy to push them further, SLAC would have already done so. These quantities are bunch length = σ_z = 2 mm, rate at which bunch pairs can be damped by 1 pair of damping rings = R_D = 180 Hz, normalized emittance = $\epsilon_n = 3 \times 10^{-5}$ rad*m ($\gamma * \sigma_x * \sigma_{x'}$), the beta function at the interaction point = β^* = 0.01 m, and the ratio of beam height to beam width = R = 1.

Other quantities are taken to be quasi-free; although these quantities may encounter practical limitations, these limitations are not precisely known and the effect of varying the quantities is explored. The quasi-free quantities are the gradient g in MV/m, the RF quality factor Q_0 (dimensionless), the duty cycle d (dimensionless), and an integer, n, which yields the RF pulse rate when it is divided into 180 Hz.

The quantity which is optimized is the capital cost plus the 10 year continuous operation electricity cost.

It is assumed that one pair of damping rings is needed for each multiple of 180 Hz or fraction thereof (in particular, that each bunch must be damped for at least 1/180 second, and that only one bunch can occupy a ring at one time). This is obviously a conservative assumption; to the extent that it is false, the cost of the pulsed superconducting 2 TeV collider described herein would be reduced. It is further assumed that the gradient in the accelerating structure should be optimized, where possible, to minimize construction plus 10-year continuous operating costs (if the machine is not operated continuously, the useful operating period is assumed to be correspondingly longer).

As shown by Richter [4], the required bunch repetition frequency is given by

$$f(\mathrm{Hz}) = \frac{414 * E(\mathrm{TeV/beam}) * \mathrm{Lum}(10^{33}\mathrm{cm}^{-2}\mathrm{sec}^{-1})}{\sigma_z(\mathrm{mm}) * \sigma_{E^*}/E^*}$$

The value of σ_{E^*}/E^* used in this equation is based on classical synchrotron radiation calculations. The classical value appropriate for use here is iteratively obtained from an approximation to the actual value [5], [6], which in turn is based on the disruption parameter D and some other parameters (the difference turns out to be unimportant for the cases of interest here). Substituting E = 1.0 TeV/beam, Lum = 1 *

10^{33}cm^{-2}sec^{-1}, σ_z = 2 mm, and σ_{E^*}/E^* (actual) = 0.01, 0.03, and 0.1, respectively, yields 20700 Hz, 6900 Hz, and 2070 Hz. Using expressions derived by Richter [4], it can be shown that

$$D^2H(D) = \frac{4*\pi*Lum*r_e{}^2*\sigma_z{}^2}{\gamma*\epsilon_n*\beta^**f}$$

where D is the disruption parameter (ratio of focal length to σ_z), H(D) is a function describing the enhancement of luminosity by the beam pinch, Lum is the luminosity (10^{37}m^{-2}sec^{-1}), r_e is the classical radius of the electron (2.818×10^{-15}m), σ_z = 0.002m, γ = 1.947×10^6, ϵ_n = 3×10^{-5} rad*m ($\gamma*\sigma_x*\sigma_{x'}$), β^* = 0.01m, and f(Hz) has one of the three values specified above. The relationship between D and H(D) yields D values of 0.534, 0.752, and 1.032, respectively. From Richter [4], knowledge of D permits N, the number of particles/bunch, to be found as

$$N = \frac{D*\epsilon_n*\beta^*}{r_e*\sigma_z}$$

This yields N values of 2.84 $\times10^{10}$, 4.00 $\times10^{10}$, and 5.49 $\times10^{10}$ particles/bunch. These are sufficiently close to the SLC bunch charge to justify an assertion that higher RF frequencies are highly undesirable for these cases.

It is assumed that 2856 MHz is an acceptable frequency, but that a higher frequency is not acceptable because of the transverse wakefields. The structure is operated in a standing wave mode, rather than a traveling wave mode, which halves its fundamental mode shunt impedance. With the present state of the art, 10 MV/m can be reached in multi-cell cavities in laboratory tests; with suitable improvements in cleanliness, the same fields should be reachable in an accelerator. With further research, it should be possible to push the gradient closer to its theoretical limit of ~50 MV/m for Nb or ~80 MV/m for Nb_3Sn. To date, the highest gradients reached at 1500 MHz have been 15.3 MV/m in a 5-cell cavity and the equivalent of 22 MV/m in a 1-cell; enhanced field emission and localized surface defects are the present field limitations, and neither of these is fundamental. Gradients obtainable at 2856 MHz are expected to be at least as high as at 1500 MHz; single cell gradients up to 31 MV/m have been reached [2]. Q_0's of 7-9 $\times10^{10}$ have been obtained in S-band cavities at Cornell, which values are substantially equal to the BCS value at the operating temperature of 1.4-1.5 K [7]. These Q_0's have not been achieved in the same tests as the highest fields, but Q_0's usually remain flat with gradient up to about 80% of the maximum gradient achievable. Further research should make these values obtainable on a more reproducible basis.

The cost terms considered are the structure (C11), refrigerator capital cost for the static heat leak (C14), refrigerator capital cost for the RF dissipation (C15), damping ring capital cost (C17), RF sources for the RF dissipation (C18), RF sources for beam power (C19), and RF sources for dumped stored energy (C21), plus 10 year static heat leak refrigeration (C12), 10 year RF dissipation refrigeration (C13), 10 year beam power cost (C16), and 10 year dumped stored energy cost (C20).

C11 = \$58,300/m [8] * .347/.303 (inflation correction)[9] * 2(linacs) = \$$1.335\times10^5$ m^{-1}.

C12 = 0.5 W/m (static heat leak) [8] * (1/0.0015) (1/refrigerator efficiency)[8] * 2 (linacs) * 8 $\times10^{-5}$ \$/(W-hour) * 24 hours/day * 365 days/year * 10 years = \$4.672 $\times10^3$ m^{-1}.

C13 = (1/2.050 $\times10^3$)(1/(Ω/m))[10] * (1/5 $\times10^{10}$)(1/Q_0) * 2 (linacs) * (1/.0015) (1/refrigerator efficiency) * 8 $\times10^{-5}$ \$/(W*hour) * 24 (hours/day) * 365(days/year) * 10(years) = 9.116 $\times10^{-11}$ \$*m/(Ω*W).

C14 = 0.5 W/m (static heat leak) * (1/0.0015)(1/efficiency) * 2 (linacs) * 5.40 \$/W [8] * .347/.303 (inflation correction) = 4.123 $\times10^3$ \$/m.

C15 = (1/2.050 $\times10^3$) (1/(Ω/m)) * (1/5 $\times10^{10}$) (1/Q_0) * 2 (linacs) * (1/0.0015) (1/refrigerator efficiency) * 5.40 \$/W * .347/.303 (inflation correction) = 8.044 $\times10^{-11}$ \$*m/(Ω*w).

C16 = 2 (linacs) * 1.6 $\times10^{-19}$ (coulombs) * 8 $\times10^{-5}$ \$/(W*hour) * (1/0.60) (1/klystron efficiency) *24 hours/day * 365 days/year * 10 years = 3.738 $\times10^{-18}$ \$*coulombs/(W*m).

C17 = 1 $\times10^7$ \$.

C18 = (1/2.050 $\times10^3$) (1/(Ω/m)) * (1/5 $\times10^{10}$) (1/Q_0) * 2 (linacs) * 1.189 \$/W (inflation-corrected CESR value: \$1.569M for 2.4 MW, * .551/.303) = 2.32 $\times10^{-14}$ \$*m/(Ω*W).

C19 = 2 (linacs) * 1.6 $\times10^{-19}$ (coulombs) * 1.189 \$/W = 3.805 $\times10^{-19}$ \$*coulombs/W.

C20 = 1.133 $\times10^{-14}$ (joules/ (m*(V/m)**2)) * 2 (standing wave enhancement) * 2 (linacs) * 1.189 (\$/watt) = 5.388 $\times10^{-14}$ (\$*sec/(m*(V/m)**2)).

C21 = 1.133 $\times10^{-14}$ (joules/ (m*(V/m)**2)) * 2 (standing wave enhancement) * 2 (linacs) * (1/0.6) (1/efficiency) * 8 $\times10^{-5}$ (\$/(watt*hour)) * 24 (hours/day) * 365 (days/year) * 10 (years) = 5.294 $\times10^{-13}$ (\$*sec/(m*(V/m)**2)).

The capital plus 10 year operating cost is given by

C = (C11+C12+C14) *E/g + (C13+C15+C18) *E*g*d + (C16+C19) *N*E*f + (C20+C21) *E*g*180/n + C17 *{int((f/(180*d))+1) OR int((f*n/180)+1), whichever is less},

where E is the energy of one linac. Taking the derivative of C with respect to g, the optimum value of g is found to be given by g = sqrt((C11+C12+C14)/((C13+C15+C18)*d+(C20+C21)*180/n)).

Some boundary conditions which must be avoided are too long an RF cycle period (the heat capacity of the liquid helium is insufficient, and a larger refrigerator is required) and too short an RF pulse (the peak power of the klystrons, rather than their average power, would determine their cost). Designs exist for 2856 MHz superconducting cavities which provide damping of the higher order modes such that the fields fall to 1/e in typically 0.33 microseconds; the bunch passage interval must not be short compared to this time.

The cost optimum for modulated linacs at particular values of f and N (average bunch frequency and number of particles per bunch) has been explored as a function of the gradient (g), the duty cycle (d), and the divisor (n) of 180 Hz (R = 180/n). For a 1% energy spread and d = 0.01, the optimum g = 51 MV/m and n = 2, assuming a Q_0 value of 5 $\times10^{10}$. For a 3% energy spread, the optimum value of g is 71 MV/m with n = 4. g = 65 MV/m is probably about the highest realistic gradient within the 80 MV/m capability of Nb_3Sn, and even that will clearly require substantial progress on field emission and point defects in order to reach it. At 65 MV/m, the optimum value of n is also 4. For a 10% energy spread, the optimum g = 103 MV/m (not reachable) and n = 9, resulting in a capital plus 10 year operating cost of 4.27 G\$ (2.61 G\$ for construction). For this energy spread and 65 MV/m, the optimum n = 8, and the construction plus 10 year operating cost is 4.55 G\$, with 3.22 G\$ for construction and 1.33 G\$ for 10 year operation. Figures 1, 2, and 3 show the cost vs. n, Q, and g for a 10% energy spread. Note that the construction cost for the machine with the 10% energy spread is quite competitive with SSC costs for a similar effective source-particle energy and the same luminosity. Also note that, if 65 MV/m at a Q of 5×10^{10} cannot be reached readily, substantially lower values result in moderate cost increases. Note that colliding linacs can be built in stages, and that new areas of physics would become accessible when only 10% of the machine had been completed.

In Figures 5 and 6, the costs for the modulated RF superconducting linac are broken down for the 10% energy spread case and 30 and 65 MV/m, respectively. The first seven bars show capital costs; the structure cost and damping ring costs are the largest of these. If it turns out to be possible to store more than 1 bunch at a time in a damping ring, or if some other method of reducing the number of damping rings required is found, the cost of the damping rings could be substantially reduced. Although use of so many damping rings (58 and 93 pairs) is not elegant, it is cost effective, and the total costs are reasonable. The next four bars on the graph show 10 year operating costs; the dumped stored energy is the

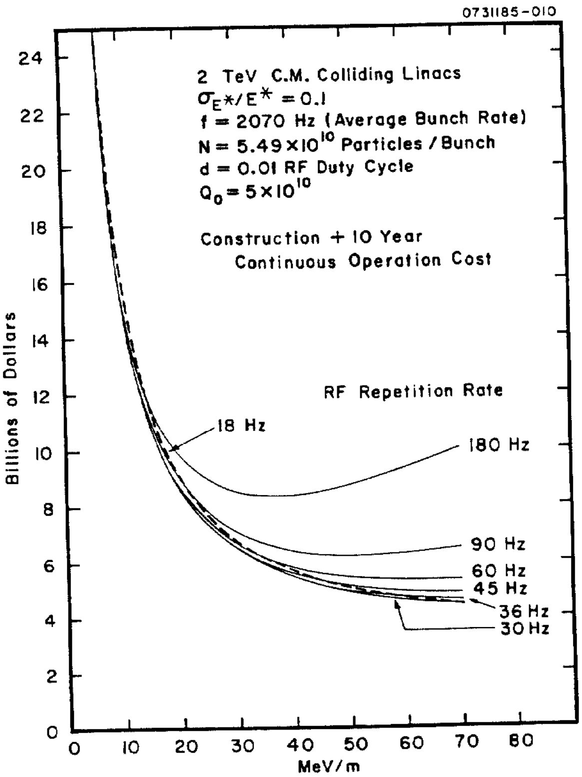

Figure 1. Cost of a superconducting, modulated, 2 TeV CM, $10^{33}cm^{-2}sec^{-1}$ collider, for a 10% collision point energy spread, vs. gradient, for various values of the modulation rate.

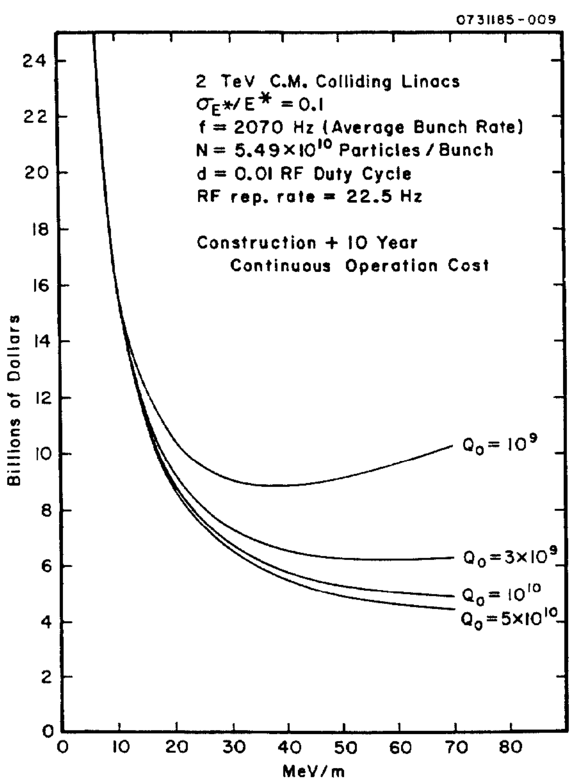

Figure 2. Cost of a superconducting, modulated, 2 TeV CM, $10^{33}cm^{-2}sec^{-1}$ collider, for a 10% collision point energy spread, vs. gradient, for various values of Q.

largest of these, even at an RF pulse rate of 36 or 22.5 Hz, and the beam power is second. The next two bars show the total capital and 10 year operating costs, respectively, and the final bar shows the sum of those two.

Table 1 shows several of the important parameters for two cases of the modulated RF superconducting linac.

Research and Development

The research and development program required to raise the

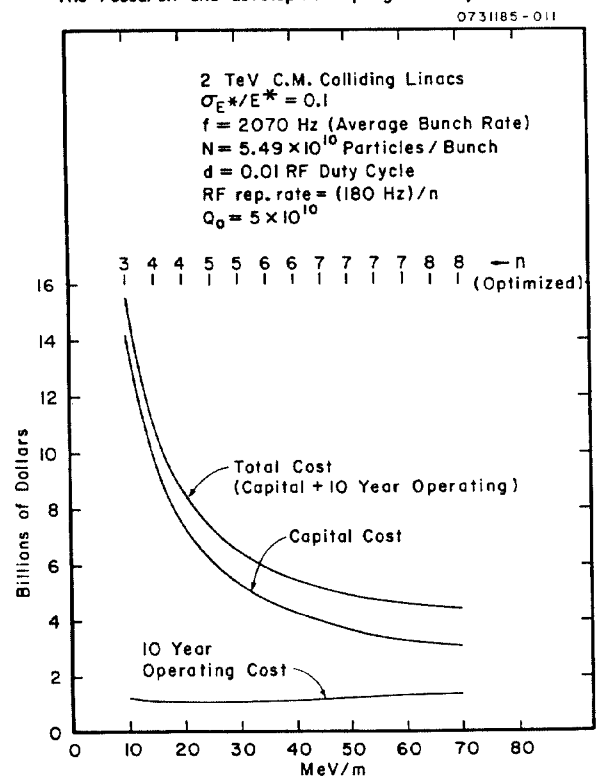

Figure 3. Cost of a superconducting, modulated, 2 TeV CM, $10^{33}cm^{-2}sec^{-1}$ collider, for a 10% collision point energy spread, vs. gradient, with the modulation rate optimized.

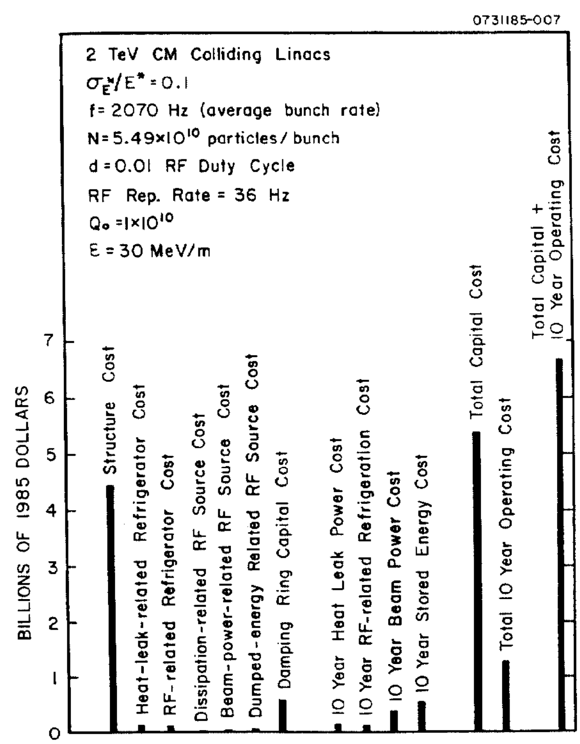

Figure 4. Breakdown of costs for a superconducting, modulated, 2 TeV CM, $10^{33}cm^{-2}sec^{-1}$ collider, for a 10% collision point energy spread, at Q = $1 \cdot 10^{10}$, and a gradient of 30 MV/m.

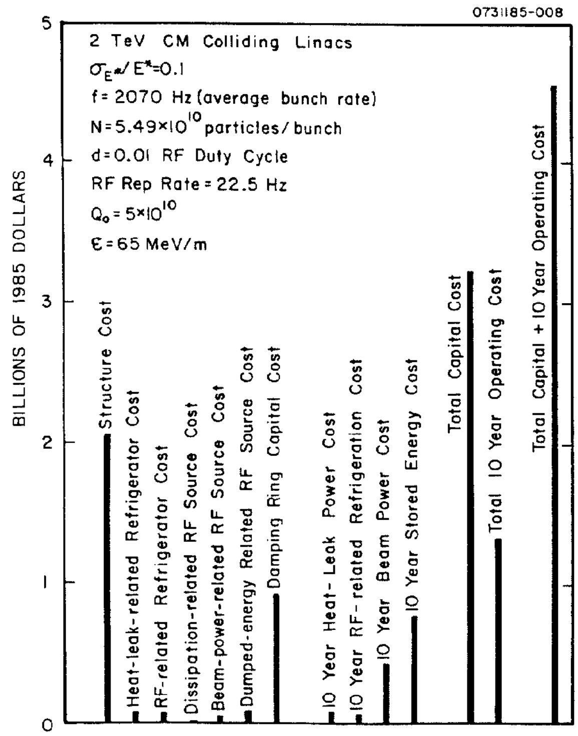

Figure 5. Breakdown of costs for a superconducting, modulated, 2 TeV CM, 10^{33} cm^{-2}sec^{-1} collider, for a 10% collision point energy spread, at Q = $5\cdot10^{10}$, and a gradient of 65 MV/m.

state-of-the-art gradients in superconducting cavities includes a study of field emission. It is well known that the field emission originates from a small number of spots where the surface behaves as though the surface field were 100 times its actual value. RF field emission can be investigated by collecting statistics on field emission in cavities which have been prepared in different ways. A second way of studying field emission consists of using a modified TM_{020} cavity with a demountable end plate; field emission sites identified by thermometry are studied in surface analytic instruments. Once the nature of the field emitters is identified, measures to suppress them can be initiated.

Hot spots on the surface are another subject requiring investigation. These spots can also be studied in cavities with demountable disks, which are subsequently examined in surface analytic instruments. Further improvements in thermal conductivity would also be useful in stabilizing the temperature of the niobium surrounding hot spots.

Although presently achieved Q's are adequate, Q's up to a factor of 20 higher would be worthwhile. Demountable end plates will again be used; in this case, areas of increased loss will be correlated with chemical or metallurgical properties using surface analytic instruments. Thermometry with a sensitivity of 1 µK is available for this work.

Designs of structures which are simpler to fabricate and less expensive will be sought. Efforts to reduce peak surface electric and magnetic fields, relative to the accelerating field, will be made.

Less expensive cryostat designs will be sought.

The applicability of materials having higher critical RF magnetic fields will be studied. Surface deposition techniques will be evaluated for coating integrity, field emission, hot spots, and surface resistance. Substrate materials will be evaluated for formability, thermal conductivity, cost, and surface layer compatibility.

Conclusion

Modulated RF superconducting colliding linacs, if the necessary gradients are reached, provide a viable way to construct a 2 TeV electron-positron collider. The importance of building a 2 TeV e^+e^- collider makes it clear that it is worthwhile for research to continue for the development of superconducting RF, in addition to other technologies capable of providing such a machine at a reasonable cost.

TABLE I

Parameter	Case I	Case II	Units
Energy (CM)	2	2	TeV
Luminosity	10^{33}	10^{33}	cm^{-2}sec^{-1}
σ_{E*}/E^*	10	10	%
β^*	1	1	cm
D	1.032	1.032	
σ_z	2	2	mm
ϵ_n	3×10^{-5}	3×10^{-5}	rad*m
g	30	65	MV/m
Q_0	1×10^9	5×10^9	
Length of RF Structure, 2 Linacs	66.7	30.8	km
RF wavelength	10.5	10.5	cm
AC power consumption	183.9	189.8	MW
Total average RF power	85.3	102.7	MW
Number of 200 kW klystrons	428	514	
Beam power	36.4	36.4	MW
Dumped stored energy	48.9	66.3	MW
RF dissipated at low temperature	17.6	7.6	kW
RF pulse rate	36	22.5	Hz
RF duty cycle	0.01	0.01	
Average beam bunch rate	2070	2070	Hz
Time between beam bunches	4.83	4.83	µs
Particles per bunch	5.49×10^{10}	5.49×10^{10}	
Number of damping ring pairs	58	93	
Capital cost	5.39	3.22	G$
10 year (cont.) operating cost	1.29	1.33	G$
Capital + 10 year cost	6.68	4.55	G$

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