Superconducting RF Linear Collider

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Abstract

The superconducting linear accelerator is characterized by a very high efficiency for converting RF power to beam power. The efficiency is independent of the resonant frequency of the structure. Because the quality factor of a superconducting cavity is high, the filling times are long, and high gradients can be achieved without high peak power RF sources. Long range wakefields associated with the high Q parasitic modes can destabilize a train of bunches. Damping of the modes via external couplers limits emittance growth in both horizontal and transverse dimensions. A simulation is used to investigate the dependence of stability thresholds on the HOM damping. The higher order mode loading typical of a 5-cell cavity with a pair of beam tube couplers is considered. We find that a beam with bunch charge of 2×10^{10} particles and bunch spacing of $100ns$ accelerated to high energy in such a structure exhibits tolerable emittance growth. The incorporation of a superconducting linac into a collider based on TLC parameters is described.

Introduction

The cost of the superconducting linear collider is dominated by that of the accelerating structure itself, the cavities and cryostat. Conventional klystrons can readily provide the peak and average power required. The length of the structure is determined by the accelerating gradient and there is an ongoing effort to attain higher gradients than have been reliably achieved to date.[1] The cost per unit length depends on the complexity of the structure and in particular on the number of penetrating RF feeds that couple fundamental power and higher order mode power through the cryostat and into the accelerating waveguide and back to loads respectively. In the optimized structure the number of feeds is minimized in accord with the need for stability.

The high efficiency of the superconducting linac for converting RF energy to beam energy is attained by the acceleration of multiple bunches in a single RF pulse. The temporal separation of the bunches in the train is limited by long range wake fields. Bunches at the head of the train excite parasitic cavity modes that interact destructively with trailing bunches. The effect of longitudinal modes is to introduce an energy spread from one bunch to the next and from head to tail within each bunch. If leading bunches in the train are displaced transversely, dipole modes are excited that can cause emittance growth of the beam. The minimum spacing of the bunches is determined by the shunt impedances and damping times for various higher order modes, the charge in the bunch, and the spread in frequencies of the resonant parasitic modes from one multicell structure to the next. A simulation is used to establish the stability limits. We find that for bunch charges of a few $\times 10^{10}$ particles that the higher order mode loading typical of multicell superconducting cavities[2] [3] permits stable acceleration with bunches spaced within as few as 100ns of each other. Equivalently we conclude that somewhat higher Q's are tolerable if the bunches are spaced further apart so that the density of higher order mode loads per unit length of linac can be reduced.

An evaluation of a superconducting linear collider is attempted by considering the insertion of such a linac between damping rings and final focus as parametrized for a TLC. The mode of operation of the superconducting linac is considered and the relevant parameters computed.

Multiple Bunch Stability

Consider a superconducting accelerating structure that consists of multiple cells (5-10), with a single fundamental power feed that couples to the beam tube at one end. In addition some number of feeds couple higher order mode power out of the structure. Again, the HOM couplers are typically located on the beam tube or end cell. Without the higher order mode couplers and loads the Q of the parasitic modes is roughly the same as that of the fundamental, and corresponding decay times are on the order of a second. The higher order modes are therefore damped to assure the stability of a train of bunches.

Transverse Stability

The coupling of the beam power into such modes is determined by the mode shunt impedance or R/Q. The frequency and impedance of the resonant modes are characteristic of the cavity geometry. The leading bunches in a train excite higher order modes. The multibunch instability can occur when the trailing bunches interact with the fields in those modes. The field induced by the bunch into a particular mode is proportional to the R/Q. The relative amplitude and phase of the fields as witnessed by the trailing bunch is determined by the frequency and loaded Q.

The investigation of the stability lends well to a computer simulation. The scenario is to track a train of bunches through a length of RF cavities with total fundamental voltage of 1 TeV (about 30km). The incremental change in the field of a dipole mode is proportional to the displacement of the bunch from the longitudinal axis of the cavity .[4]

$$\Delta \mathbf{E}_\perp(t) = q\left(\frac{R}{Q}\right)\frac{c}{2}\frac{\mathbf{x}}{a^2}\sin\omega_n t\; e^{-\omega_n t/2Q_n}. \qquad (1)$$

$\mathbf{x}$ locates the bunch with respect to the axis and a is the radius of the iris of the cavity. ω_n and $(R/Q)_n$ are the frequency and R/Q for the n^{th} mode. The full length of the linac is subdivided into a large number of cavities (10000) of length l_0 with which the beam interacts impulsively. The R/Q is therefore the shunt impedance per unit length l_0. q is the bunch charge.

The transverse field in the n^{th} mode witnessed by the m^{th} bunch in the train due to all previous bunches is

$$\mathbf{E}_{nm} = q\left(\frac{R}{Q}\right)_n \frac{c}{2a^2}\sum_{i=1}^{m}\mathbf{x}_i \sin\omega_n(t_m - t_i)\; e^{-(t_m-t_i)\omega_n/2Q_n}.$$

The total field is given by the sum over all modes

$$\mathbf{E}_m = \sum_n \mathbf{E}_{nm}.$$

Here t_i and t_m are the times at which the i^{th} and m^{th} bunches exchange energy with the particular cavity and if the bunch spacing is a fixed time τ we can write

$$\mathbf{E}_{nm} = q\left(\frac{R}{Q}\right)_n \frac{c}{2a^2} Im\sum_{i=1}^{m}\mathbf{x}_i e^{\omega_n(m-i)\tau(j-1/2Q_n)}.$$

$$= \mathbf{E}_{nm} = Im\left[\mathbf{E}_{n,m-1}e^{\tau(j-1/2Q_n)\omega_n} + \left(\frac{R}{Q}\right)_n \frac{qc}{2a^2}\mathbf{x}_m\right].$$

The interaction of the bunch with the cavity includes a transverse kick due to the existing field as well as the incremental addition to the field in the mode. We assume the equivalence of vertical and horizontal transverse modes and consider only the motion in a single transverse dimension. Then we can abbreviate $\mathbf{x_m} \to x_m$ and the trajectory of the bunch is described by (x, x'), its displacement and angle with respect to the axis of the linac. The change in x'_m for the m^{th} bunch due to the interaction with transverse fields in the n^{th} mode is $\Delta x' = \frac{eE_{nm}}{cp_{beam}}$. Then $(x, x') \to (x, x' + \Delta x')$. The trajectory at the next cavity in line is given by a phase space rotation.

$$\begin{pmatrix} x \\ x' \end{pmatrix}_{cavity\ k} = R(\beta, \phi_\beta)\begin{pmatrix} x \\ x' \end{pmatrix}_{cavity\ k-1}$$

where β and ϕ_β are the betatron function and phase advance from one impulsive cavity interaction to the next.

For the purpose of the simulation the source of the transverse instability is presumed to be jitter associated with the injection of the low energy bunch train onto the axis of the linac. Here transverse motion of a leading bunch translates to a transverse

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kick of a trailing bunch. We introduce a gaussian distribution of errors in the phase space coordinates of the injected bunches. The bunches are tracked through the linac in sequence and the phase space distribution recomputed at full energy. The bunch is treated as a macroparticle so of course there is no emittance associated with the individual bunch. Rather the phase space for the entire train is computed. The growth in transverse phase space is then just the ratio of the normalized beam size at the final linac energy and at the injection energy,

$$R_{f/i} = \sqrt{\frac{\epsilon_n(E_{final})}{\epsilon_n(E_{initial})}}. \tag{2}$$

In the absence of wakefields the ratio (2)is unity. The β function is assumed to be uniform from the injection point through the end of the linac and the phase advance per cell non-integral.

A growth in transverse amplitude is not an emittance blowup of single bunches but rather of the beam as a whole. The blowup due to a single mode is computed as a function of bunch charge, loaded Q for the parasitic mode, and mode frequency spread. In general the mode frequency varies from one cavity to the next due to fabrication tolerances. Whereas the fundamental is precisely tuned, the higher order modes tend to assume some spread about the nominal which is included in the simulation by a gaussian distribution of frequencies for the mode.

The cavity codes, URMEL and URMELT[5] yield frequencies and coupling parameters for higher order modes in the 5-cell s-band π-mode structure as a representative model for the accelerating cavity. The maximum geometrical coupling into a transverse mode is $(\frac{R}{Q}) = 1.3 \times 10^6 \Omega/m^3$ The simulation of the effects of a single mode is based on this maximum value. Note in any case that according to (1)the dependence on $(\frac{R}{Q})$ is equivalent to the dependence on charge.

Single Transverse Mode

The results of the simulation of transverse beam emittance growth due to a single higher order mode are indicated in Fig. 1 and 2. The bunches are spaced $1\mu s$ apart. There are 500 bunches in the train. The frequency spread can sometimes effect the stability in so far as it can undermine a resonant buildup of the fields. But we find that in the case of a single cavity mode interacting with bunches with random transverse phase space coordinates that the emittance growth is independent of bandwidth.

If we suppose that the magnitude of the phase space jitter introduced at the injection point is on the order of 10% of the bunch emittance then we can perhaps tolerate a factor of two growth before there is a significant degradation of the luminosity.

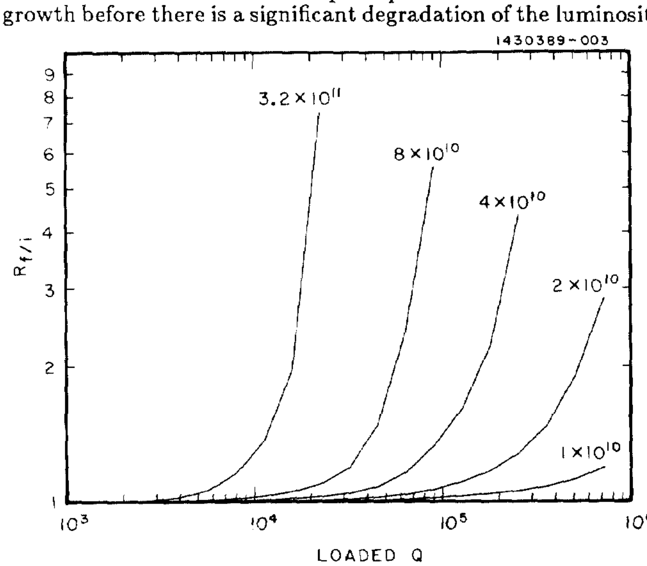

Fig. 1. The ratio $R_{f/i}$ defined in (2)is shown as a function of the loaded Q of the mode. The mode impedance is $(\frac{R}{Q}) = 1.3 \times 10^6 \Omega/m^3$. The beam emittance growth is indicated for several values of the bunch charge.

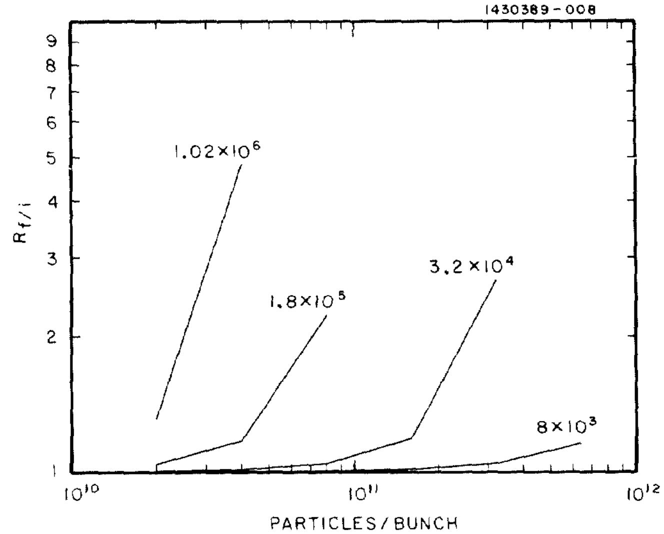

Fig. 2. The ratio $R_{f/i}$ is shown as a function of the bunch charge. The beam emittance growth is indicated for several values of the loaded Q.

We see that a beam of bunches with 2×10^{10} particles, spaced $1\mu s$ apart is stable for $Q < 5 \times 10^5$ and that if the $Q = 3.2 \times 10^4$ that the beam is stable if there are less than 3×10^{11} particles.

Ten Transverse Modes

In a typical multicell structure with higher order mode couplers located in end cell or beam tube, there is a wide variation in loaded Q among modes. It is useful to consider the implications for stability of a distribution of modes, impedances and loaded Q's and for that distribution we use measured values in a real structure, the 5 cell 1.5 GHz cavity developed for CEBAF. There are approximately 20 transverse modes with frequencies below the beam tube cutoff.[2] The simulation is based on the 10 highest impedance modes. Frequencies and impedances are scaled to $3Ghz$. All measured frequencies double and the impedances scale by the cube of the ratio of the frequencies. The stability $R_{f/i}$ is computed as a function of the bunch charge, bunch spacing, and the mode frequency spread. The spread is here defined by a gaussian distribution of frequencies of fractional width $\Delta f/f$. There are 100 bunches in the train.

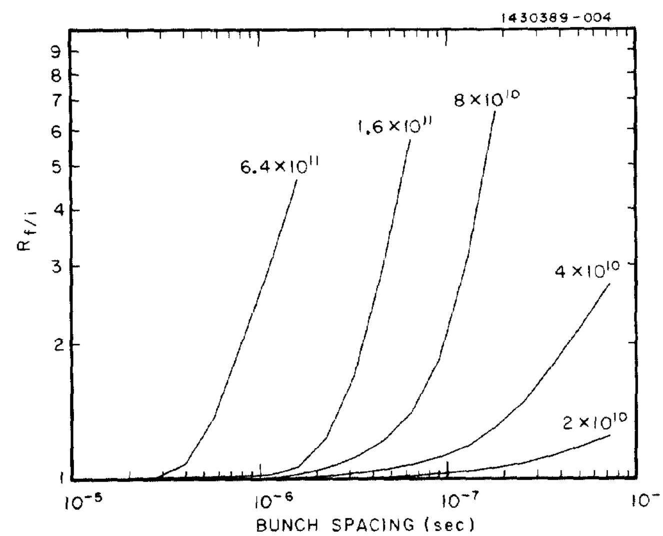

Fig. 3. The ratio $R_{f/i}$ is shown as a function of the bunch spacing for several values of the charge. The mode bandwidth is $\Delta f/f = 2 \times 10^{-5}$. There are 10 distinct modes in each cavity.

It is clear from Fig. 3 that a beam of bunches with $\sim 5 \times 10^{10}$ particles spaced as few as $100ns$ apart is stable in a linac assembled from 5-cell, CEBAF-like cavities with a single pair of HOM loads coupled via the beam tube. An increase in the Q of the ten modes is equivalent to a decrease in the time between bunches. Apparently it is possible to relax the cavity loading and to increase the bunch spacing. For example, according to Fig. 3, a beam with 2×10^{10} particles in bunches spaced $1\mu s$ apart can be accelerated without intolerable emittance growth even if the loaded Q in each of the ten modes is increased by two orders of magnitude. In a collider based on similar beam parameters it is evident that the number of cells per higher order mode coupler will be very much more than five.

In the case of multiple modes per cavity the nonzero bandwidth can be important if the phase advance between bunch passages is otherwise identical in all of the modes. If for example all of the frequencies are specified to only a few decimal places then $\omega_n \tau = 2m\pi$ where m is an integer for all modes n and all modes add coherently. The introduction of even a very small frequency spread spoils the coherence.

Longitudinal Multibunch Stability

The fields associated with higher order longitudinal modes are generally out of phase with that of the fundamental accelerating mode. Then the effective accelerating voltage will be a superposition of the fields in the higher order modes. It can vary from bunch to bunch and from head to tail within each bunch. The energy bandwidth of the final focus in a TeV collider is typically narrow and it is therefore important to preserve a small energy spread in the beam particles.

To be sure there are other factors that effect the energy spread within each bunch, including the short range wake of the head of the bunch on the tail, the change in the field of the unloaded fundamental from head to tail, and the spread associated with the longitudinal phase space at the exit of the damping ring. Indeed it is generally anticipated that some head tail energy difference is deliberately introduced to control emittance growth due to short range transverse wakes.[6] A phase adjustment of the fundamental near the end of the linac will presumably compensate the spread imperfectly. But here we consider only the consequence of high Q parasitic modes.

Each bunch adds an increment of field to each higher order longitudinal mode.[4]

$$\Delta E_{\parallel}(t) = q\frac{\omega_n}{2}\left(\frac{R}{Q}\right)_n \cos\omega_n t \; e^{-\omega_n t/2Q_n}.$$

The change to the field depends only on the bunch charge and arrival time, neither of which can be effected by the interaction with the fields in upstream cavities. This is of course very unlike the case of the transverse wake.

Again we base the calculation on 5 cell elliptical geometry at s-band. The R/Q in the TM010 fundamental accelerating mode is $1919\Omega/m$. Of all the parasitic longitudinal modes, the strongest coupling occurs for a member of the TM011 passband with $\frac{R}{Q} = 494\Omega/m$. Other modes have at most 10% of the impedance of the TM011. The study of the longitudinal stability begins with a similation that includes a single mode just as for the transverse case. A train of bunches is tracked through the linac and in each section (we subdivide the linac into 3000-sections) the fields in the mode(s) are incremented. The charge is distributed between a head and tail with a temporal separation corresponding to a bunch length of $1mm$. The voltage in the mode is computed at both the head and tail. For simplicity it is assumed that the field added by the bunch is not available for interaction with the head but entirely for the tail.

We compute the average bunch energy, and the average energy difference of head and tail. We suppose that: the final focus is optimized for the average bunch energy, and that the average difference in energies of head and tail is compensated by accelerating off the crest of the fundamental. The spread in the energy from bunch to bunch is not so readily compensated and we compute the width of the distribution. The normalized beam energy width

$$\sigma^n_{beam} = \frac{1}{E_{final}}\sqrt{\sum_{i=1}^{N}(< E > -E_i)^2}, \qquad (3)$$

and the normalized bunch energy width

$$\sigma^n_{bunch} = \frac{1}{E_{final}}\sqrt{\sum_{i=1}^{N}(< \Delta E > -\Delta E_i)^2} \qquad (4)$$

where $< E >$ is the average of the energies E_i, $< \Delta E >$ is the average of the head tail energy differences $\Delta E_i = E_{i\ head} - E_{i\ tail}$, and E_{final} is the final beam energy. The sum is over all of the bunches.

The normalized beam and bunch energy widths as defined in (3)and (4)are computed for the case of a single mode as a function of bunch charge, loaded Q, and the mode bandwidth. The bunch spacing is fixed at $1\mu s$ and the mode $R/Q = 494\Omega/m$.

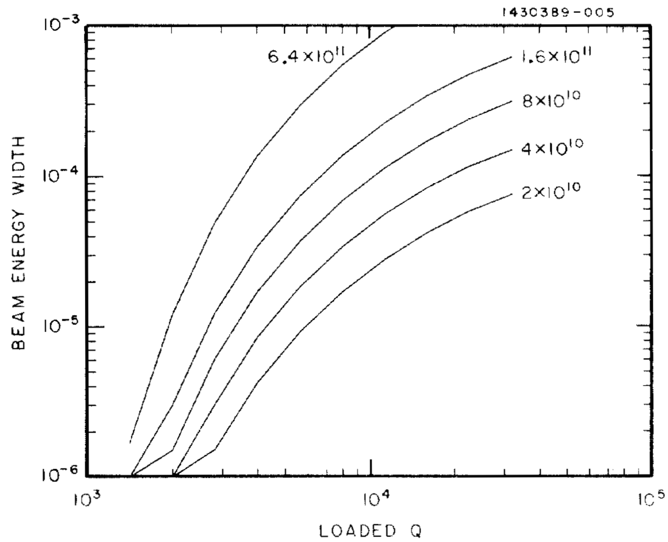

Fig. 4. The normalized beam energy width σ^n_{beam} is shown as a function of loaded Q for different values of the bunch charge. The mode bandwidth $\Delta f/f = 2 \times 10^{-5}$.

We see from Fig. 4 that for relatively small bunches and $Q < 3 \times 10^4$ the beam energy spread is less than a part in 10^4. Because the phase of the incremental field change depends only on the time between bunch passages, and because that time is fixed, there is a sensitivity to the bandwidth of the mode as shown in Fig. 5. The bunch energy width, $\sigma^n_{bunch} < 10^{-5}$ for all values of charge and Q.

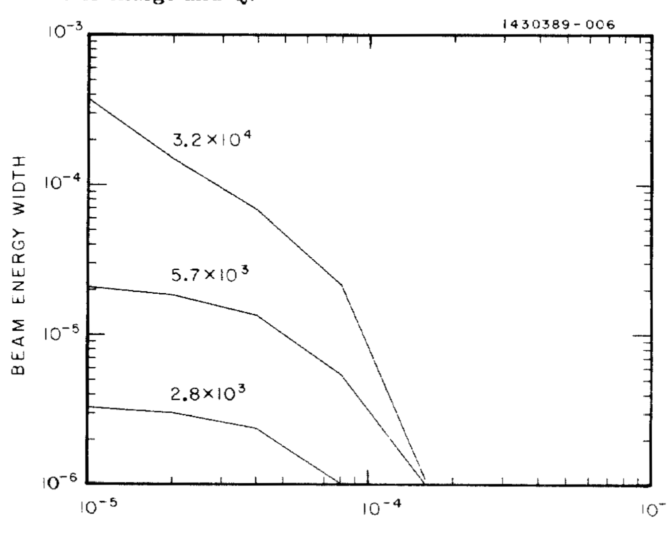

Fig. 5.σ^n_{beam} is shown as a function of the bandwidth for different values of the loaded Q for 4×10^{10} particles per bunch.

Ten Longitudinal Modes

Again it is useful to investigate the effects of multiple modes based on measurements in an existing structure. As before the frequencies and impedances in the ten modes with the largest coupling as measured in the 1.5GHz 5-cell are scaled to 3 GHz. We compute the beam and bunch energy width as a function of bunch charge, the frequency spread in each mode from one cavity to the next, and the bunch spacing. The beam energy spread is shown in Fig. 6 as a function of the bunch spacing. Except for the very highest values of the bunch charge, the width of the distribution of normalized bunch energies is less than 10^{-5} which is very small indeed as compared to energy spread due to other effects. The typical TLC final focus is tolerant of an energy spread of about 0.1% .[7]

As in the case of the transverse modes, in a linac with bunches with 2×10^{10} particles spaced $1\mu s$ apart, the loading can be relaxed by at least an order of magnitude with respect to that of the CEBAF 5-cell.

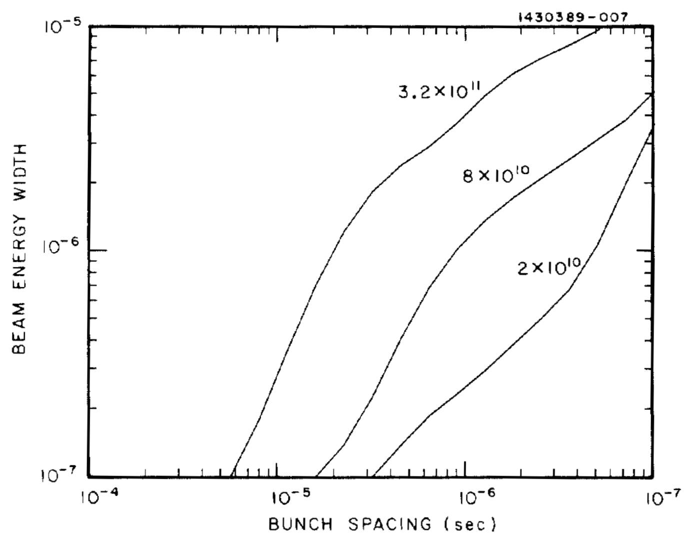

Fig. 6. The normalized beam energy width σ^n_{beam} is shown as a function of bunch spacing for various values of the bunch charge. $\Delta f/f = 2 \times 10^{-5}$. There are ten modes in each cavity.

Linear Collider

In the linear collider very low emittance bunches of electrons and positrons are accelerated in opposing linacs to high energy and brought into a violent collision. The disruption of the bunches generally precludes recovery of either beam charge or energy. The luminosity per unit bunch charge is necessarily high (by storage ring standards) so that the beam power is affordable. The three essential building blocks of the machine are:

1. A source of low emittance bunches of electrons and positrons (damping rings),
2. The linear accelerator,
3. The final focus.

We would like to investigate the properties of a collider in which the linac is superconducting without having to invent an entire parameter list. A self consistent set of machine parameters has been developed for a TLC[7] and the three components examined in some detail. We simply substitute a superconducting linac for the room temperature TLC structure. Beams generated in sources very similar to those of the TLC are accelerated in the superconducting linac to 0.5TeV. The high energy beams can presumably be transported through the final focus if the transverse emittance growth and wakefield induced energy spread are within the TLC design tolerances. Collisions then yield the appropriate luminosity.

The parameters relevant to the operation of the linac are the bunch charge, bunch length, repetition rate and final beam energy. In a TLC design[7] we find $N_{bunch} \sim 1.5 \times 10^{10}$, $\sigma_z \sim 70\mu m$, $< f_b >= 3.6kHz$, and $E_{beam} = .5TeV$.

RF Wavelength

Our choice of 3 GHz for the RF frequency of the superconducting linac is somewhat arbitrary. Higher frequencies offer possible advantages:

1. Fabrication costs may be lower since the cavities and cryostats are smaller.
2. The lineal shunt impedance is proportional to the frequency and therefore the power dissipated in helium for a given gradient scales inversely with frequency.

There are several significant disadvantages to higher frequencies.

1. The BCS losses in the walls of the cavity increase $\sim \omega^2$ and higher frequencies generally imply lower operating temperature. At frequencies much higher than 3GHz the operating temperature would necessarily be below $1.5K$ which would dramatically increase the capital cost of the refrigerator.
2. The loaded Q in the higher order modes is determined by the number of cells per coupler. The number of cells per input coupler is similarly independent of wavelength. Therefore the number of RF feeds and cryostat penetrations per unit length of linac is proportional to frequency.
3. The longitudinal wakefields grow with the square of the frequency for very short bunches, and the transverse wakefields as ω^3.

In a 3GHz niobium cavity the Q is dominated by residual losses (frequency independent) at the manageable temperature of 1.5K. It is demonstrated in the SLC that bunches with a charge of few $\times 10^{10}$ particles can be successfully transported through an S-band linac. The length of a superconducting multicell cavity is perhaps constrained by fabrication techniques such as electron beam welding and chemical polishing and a very large structure ($> 1m$) becomes unwieldy. If each module is no longer than 1 meter, then there is a minimum of one input power coupler and one output HOM coupler per meter. In S-band structures operating in the π-mode there are 20 cells per meter. The stability calculations described above suggest that a loading of one coupler per 20 cells may indeed be optimal. S-band appears to be a reasonable choice for the structure wavelength.

Pulse Width and Duty Cycle

We assume that the accelerating gradient of the linac is 40 MeV/m with unloaded $Q_0 = 4 \times 10^9$ and that in the accelerating mode $(\frac{R}{Q}) = 1919\Omega/m$. The parameters are typical of superconducting cavities except for the gradient. As in the case of the TLC the mode of operation of the linac is to pulse the RF, accelerate a train of bunches, and then dump the stored energy. Between pulses a fresh train of bunches is cooled. In the interest of minimizing the amount of dumped stored energy it is best to have a few pulses of long duration. But we assume that the yield from each TLC damping ring is 100 bunches at any given time. It is clear from Figs. 2 and 6 that with $N = 1.4 \times 10^{10}$ that a 100ns bunch spacing is tolerable. We extend the spacing to $1\mu s$ anticipating a cost saving due to the relaxation of the higher order mode damping. Then 100 equally spaced bunches imply a 100 μs RF pulse. In order that the pulse length not be short compared to the fill time as well as to reduce the amount of dumped stored energy we suppose that two TLC damping rings are available and that 200 bunches are accelerated in a $200\mu s$ pulse. Note that the damping rings will differ from those in the TLC design in that bunches are extracted one at a time rather than in batches of ten[8] . Kicker requirements are somewhat different.

RF Power

The beam loaded $Q_L = \frac{E^2_{acc}}{(R/Q)\bar{P}_{beam}} = 3.6 \times 10^6$, where E_{acc} is the accelerating voltage and $\bar{P}_{beam}$ the peak beam power. The cavity filling time $\tau_f = \frac{2Q_L}{\omega}$ and the time to fill to the beam loaded equilibrium voltage is $\tau_e = 263\mu s$. The peak power required of the klystron is $P_{peak} = U/\tau_e = \frac{E^2_{acc}}{(R/Q)}\frac{1}{\tau_e} = 168kW/m$.

At the end of each pulse the energy stored in the cavities is dumped. $P_{dumped} = Uf_{RF}$ where f_{RF} is the RF repetition rate. The total RF power $P_{total} = P_{dumped} + P_{beam}$ and $P_{beam} = eN_{bunch}E_{final}f_b$. The corresponding wall plug power includes a klystron efficiency which we take to be 60%. Since the Q_0 is three orders of magnitude greater than the beam loaded Q_L, there is negligible power required to establish the gradient.

Refrigerator Power

The total power dissipated at low temperature includes losses in the fundamental accelerating mode, higher order mode power, and the static heat leak. Power is dissipated in the fundamental since the Q is after all finite.

The program BCI[9] is used to compute the total loss parameter k. Then the higher order mode power $P_{HOM} = kq^2 f_b$. Some fraction of the energy is extracted through the higher order mode couplers, but even for a relatively long $1mm$ bunch this accounts for only about 15% of the total power. The remainder of the energy is in modes with frequencies well above the accelerating waveguide cutoff. Some of it will surely be dissipated at low temperature and some in the normal conducting transition sections. We assume that 50% of the total HOM power is dissipated in helium.

The loss parameter is a sensitive function of the bunch length. We compute $k(\sigma_z = 250\mu m) = 4.3$ Volts/pico-Coulomb. Calculations of the loss parameters for shorter bunches are not yet completed. But based on the computed wake potential for the SLAC s-band structure,[4] we estimate that $k(\sigma_z = 70\mu m) \sim 6.5$ Volts/pico-Coulomb.

The typical static heat leak in existing superconducting $500Mhz$ cavities is about $5W/m$. We assume a factor of five improvement by virtue of the smaller stucture and fewer cryostat penetrations. The total refrigerator power

$$P_{ref} = (P_{fund} + P_{HOM} + P_{heat\ leak})/\epsilon_{ref}$$

where $\epsilon_{ref} = 20\%\epsilon_{carnot} = 0.001$ at $1.5K$. The linac parameters are summarized in the table. The power is for both electron and positron beams.

Linac Parameters	
Particles/bunch	1.4×10^{10}
Bunch Length	70 μm
RF frequency	3Ghz
R/Q fundamental	1919.8 Ω/m
Accelerating gradient	40MeV/m
Final beam energy	0.5TeV
RF rep rate	18 Hz
RF pulse width	200×10^{-4} seconds
Bunches per pulse	200
Bunch spacing	10^{-6}seconds
Beam Power	8.07MW
Dumped Stored Energy	19.9MW
Total RF/klystron eff	46.7MW
Peak RF power	168kW/m
Fundamental power at 1.5K	7.2kW
HOM power at 1.5K	32kW
Static heat leak at 1.5K	12.5kW
Refrigerator power	51.7MW
Total wall plug power	98.4MW

Insofar as the linac described can accelerate the relevant TLC bunched beam to high energy and preserve the low emittance we have a self consistent parameter set for a machine with luminosity in excess of $10^{34}cm^{-2}s^{-1}$. We find that the wall plug power requirements are reasonable and that existing klystrons can satisfy the modest peak power demand.

The superconducting linear collider has other benefits with respect to the TLC high frequency room temperature design as a consequence of the strong dependence of wakefields on structure size. Transverse wakefields scale as $W_\perp \sim \omega^3\sigma_z$. Alignment and injector tolerances are thus significantly relaxed as compared to the short wavelength alternative. Bunches with numbers of particles similar to those considered here but with several times the length have been accelerated in the SLAC s-band linac demonstrating transverse stability with respect to short range wakes.

The longitudinal wake $W_\parallel \sim 1/a^2$ for bunches short as compared to the wavelength[10] where a is the radius of the iris. In consequence the energy spread of the full energy bunch is very much smaller in the superconducting linac than in the standard TLC scenario. The energy bandwidth of the final focus can be narrower in the low frequency machine permitting larger quadrupole apertures and perhaps precluding the need for crossing angles and related complications. Since wakes are not severe, higher bunch charge and larger emittances become practical alternatives.

The machine is defined in terms of the TLC bunched beams and final focus and an s-band superconducting linac. There has been almost no attempt to adjust the beam parameters to match the characteristics of the superconducting linac. For example a beam of longer bunches is advantageous in terms of total higher order mode losses. And an increase in the number of bunches per pulse and corresponding decrease in RF repetition rate reduces the dumped stored energy. An optimized parameter list may prove quite different.

Gradient

The key to the realization of a high energy superconducting linac is high gradients in a practical accelerating structure. At present electron field emission limits the peak surface field that can be supported in superconducting cavities. Surface treatments including high temperature annealing and pulse power processing are being investigated.[11][12] High vacuum heat treatment has been shown to reduce the number of field emitters and to yield peak surface fields in excess of $50MeV/m$ in single cells. With the attainment of accelerating gradients of $30-40MeV/m$ in a multicell cavity the superconducting linear collider will become a very attractive alternative indeed.

Conclusion

The emittance growth and energy spread due to high Q parasitic modes is computed as a function of bunch charge, loaded Q, and mode bandwidth. Once the beam parameters are specified the maximum value for loaded Q, or alternatively the bunch spacing is determined. For beams typical of linear colliders based on normal conducting cavities, we find that existing multicell cavities are over damped. The maximum number of cells per higher order mode coupler is at least greater than five. A 3Ghz superconducting linac can be incorporated very simply into a design for a high energy linear collider.

Acknowledgement

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