Linear Collider Applications of Superconducting RF*

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Introduction

The most promising technology for producing interactions of electrons and positrons in the TeV energy range is the linear collider. In the linear collider each and every collision of charged particles depends on the production of the charges at rest and then the acceleration of those charges to full energy. The particles that exit the interaction region are discarded. A consequence of this mode of operation is that the luminosity of the machine is ultimately determined by the efficiency with which AC power can be converted into beam power. The consideration of superconducting cavities is motivated by the need for high efficiency.

Conceptual designs of machines that use superconducting cavities can help to identify the outstanding technical challenges. Parameter lists have been generated by Sundelin and Amaldi et. al. that are based on the collisions of round beams. Recent developments in the conceptual design of damping rings and final focus systems for conventional (room temperature) linear colliders exploit flat beams. We review the designs for superconducting round beam machines and then discuss the characteristics of a flat beam source and interaction region. The results of an analysis of the stability of the flat beams in an s-band high Q linear collider are presented, where the bunch charge and repitition rate are chosen to yield $L \sim 10^{34} cm^{-2} s^{-1}$ at $E_{CM} = 1TeV$. The operational characteristics of the superconducting linac with flat beams are summarized. Finally there is a brief review of a superconducting drive linac for a "two-stage" accelerator.

High Emittance Round Beam Collider

In a linear collider bunches of electrons and positrons are accelerated to high energy in opposing linacs and brought into violent collision. The severity of the beam-beam interaction limits the recovery of the beam particles and energy. In a low frequency (s-band) linac the fraction of the cavity stored energy that is extracted by a bunch is very small and typically less than 1%. A straightforward extrapolation of SLC techniqes by an order of magnitude in energy (by lengthening the linac) and several orders of magnitude in luminosity (by increasing the repitition rate) leads to a machine that is prohibitively expensive to operate. The standard conceptual approach to improving the efficiency of the linac is to reduce its volume (higher frequency) and then increase the accelerating gradient (both to ameliorate the effect of the transverse wakefields and to reduce the overall length of the machine.) The stored energy can be used even more effectively if many bunches are accelerated in each RF pulse. The efficiency or the ratio of the energy

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extracted by the beam to the stored energy in the cavity is

$$\eta = \frac{en_b N \omega^2 \frac{r}{Q}(\omega_0)}{E_{acc}^2} \tag{1}$$

where n_b is the number of bunches, N is the number of particles per bunch, $\frac{r}{Q}(\omega_0)$ the shunt impedance per unit length evaluated at ω_0 and E_{acc} the accelerating gradient. It is clear from (1) that efficiency increases rapidly with the total charge and the frequency. The inclination toward higher RF frequency to reduce the required AC power has other implications. Transverse wakefields tend to cause emittance growth in single bunches and destabilize trains of bunches. The transverse kicks scale as $\frac{\Delta p_\perp}{p} \sim 1/(a_2 n_{cell}) \sim \omega^3$ where a is the radius of the accelerating cell iris and n_{cell} is the number of cells per unit length. The consequence is very severe alignment and kicker tolerances, introduction of a substantial energy spread in the bunches in order to exploit BNS damping, and the need for very heavy damping of transverse modes[1] ($Q_L < 20$) to preserve the integrity of the bunch train.[2] BNS damping has proved effective at controlling emittance growth in the SLC at s-band .[3] Paper designs for very high energy linacs rely on a five to ten fold increase in RF frequency.

Another complication associated with the high frequency and high gradient copper structure is the RF source. The pulse length scales with frequency according to $\tau \propto \omega^{-\frac{3}{2}}$, and the power with the square of the gradient. The peak power required of the source is very high. The development of reasonably priced, high frequency, high peak power sources is perhaps the most challenging aspect of the room temperature linear collider technology.

A superconducting linear accelerator is characterized by a high efficiency for converting stored energy into beam energy. In a high Q structure the fill time is long and peak power requirements are modest. Using external HOM loads it is possible to achieve decay times many orders of magnitude shorter in destabilizing modes as compared to the fundamental mode so that relatively dense trains of bunches can be accelerated in each RF pulse. The efficiency of the superconducting accelerator is only weakly dependent on RF wavelength and can be based on large aperture cavities with tractable wake field properties. Such a linac can by virtue of a lower operating frequency have very much simpler alignment tolerances. The threshold bunch charge for transverse emittance growth can be more than an order of magnitude higher than in a high frequency copper structure. The disadvantages of the fully superconducting machine include the relatively low limit on accelerating gradients imposed by field emission, the refrigeration and cryogenics required to cool the cavities and the associated high cost of the structure.

Sundelin's[4] design is based on the acceleration of bunches with emittances, charge, and length very similar to those of the SLC. The normalized emittance is $\sim 3 \times 10^{-5} m - rad$, $N \sim 5 \times 10^{10}$ and $\sigma_z \sim 1mm$. The final focus is also much like the SLC final focus in so far as the beams are round and $\beta \sim 1cm$. The superconducting linac is chosen to operate at 3Ghz and a gradient of at least 30MV/m. The viability of the single bunch dynamics is therefore already demonstrated by the SLC performance. In particular, the proscribed bunches have been generated in the SLC damping rings and accelerated with tolerable emittance growth through an s-band linac with a gradient of about 20MV/m. In the design example multibunch instabilities are controlled by loading the parasitic cavity modes so that there are at least five decay times between bunch passages. It is pointed out that the required loaded Q's of about 10^4 are readily obtained in four and five cell structures.

The operating mode of the machine is similar to that of a copper linac. The cavities are filled with RF energy, a train of bunches is accelerated, and then the stored energy is dumped at room temperature. As distinct from the room temperature structure, the duration of the pulse is several hundred microseconds instead of $\sim$ 100 nanoseconds because the Q of the accelerating mode is $\sim 10^9$ in the superconducting cavities and $\sim 10^4$ in copper. Therefore the bunches can be spaced nearly 1000 times further apart in the high Q linac. The number of bunches that can be accelerated without multibunch instability scales as the ratio of the Q of the accelerating mode to that of the higher order parasitic modes. In a superconducting cavity with HOM couplers the ratio is $\frac{Q_0}{Q_{HOM}} \sim 10^5$. In a heavily loaded copper structure it may be possible to obtain a ratio of at most $\frac{Q_0}{Q_{HOM}} \sim 1000$. The number of bunches and the fraction of energy extracted from each RF pulse is very much higher in the superconducting linac.

The duration of the RF pulse is limited by the refrigerator power required to carry away the power dissipated in the cavity walls. If the $Q_0 \sim 3\times10^9$ and the duty cyle about 1%, the refrigerator power is considered acceptable($\sim 10-20MW$). If the frequency of pulses is high then the cost of stored energy dumped at the conclusion of each pulse is also high. Alternatively,.a long pulse demands a high peak rate from the damping ring source. In a single pulse mode with a very long bunch train all of the bunches are necessarily damped simultaneously in one large or several small rings. If the pulses are short then so is the bunch train required to fill it. Apparently there is a reasonable optimum if the RF is pulsed at 20Hz and the length of each pulse is about 500μsec. The average bunch repitition rate is 2kHz.

The design is based on relatively conservative SLC beam parameters. The beam power is high $\sim 40MW$ and the luminosity at 2TeV center of mass energy is $10^{33}cm^{-2}s^{-1}$. Suitable accelerating sructures have $Q_0 \sim 3\times10^9$, $Q_{HOM} \sim 10^4$, and $E_{acc} \sim 30MV/m$. Except in terms of gradient the requirements are consistent with existing capabilities. SLC performance demonstrates the viability of the beam parameters.

Low Emittance Round Beams

Amaldi et.al.[5] parametrize a machine with somewhat higher luminosity and lower beam power. This is achieved by supposing that the round beams have an order of magnitude smaller emittance in both dimensions, that β^* is reduced 10 fold with respect to the SLC and that the quality factor of the cavities is well over 10^{10}. The machine can then operate with a duty cycle over 10% and an average bunch repitition rate of nearly 100kHz. There are 100 times fewer particles in each bunch ($N \sim 6.5\times10^8$) and the cavity frequency is 1Ghz so that transverse wakefields are very much weaker than in the SLC. The bunch spacing can thus be significantly reduced and this is exploited in the configuration of the source. In order to damp the large number of bunches required to fill the RF pulse, the bunches are grouped in trains of 10 where the interbunch spacing is the RF wavelength (30cm). The trains are spaced about 7m apart. Then about 500 bunches can be damped in each damping ring cycle as compard to only two in the SLC damping rings. The beam power again at 2TeV center of mass energy is about 10MW.

In an alternative mode of operation the authors consider a scheme in which the spent beam is decelerated and its energy is recovered in the opposing linac. The recovery is effective only if the beam is relatively intact after its collision. The violence of the collsion can be characterized by the beamstrahlung induced energy spread. In the machine without energy recovery the beamstrahlung parameter is $\delta = 0.1$. If their is energy recovery it is supposed that the beamstrahlung will have to be reduced to $\delta = 0.01$. If 90% of the energy is recovered then the beam power can be increased by an order of magnitude (to 100MW) without a corresponding increase in wall plug power. The pay off is that it is not necessary to have such low emittance in order to gain high luminosity. An outstanding complication is the stability of the decelerated beam and the ultimate fate of the 10MW that is not recovered. In addition since the bunch spacing is small (the average repitition rate is greater than 100kHz), there will be multiple collision points of electrons and positrons along the length of each linac. In both recovery and non recovery modes the cavities are required to have very high Q as well as high gradient. Due to the high repitition rate the demands on the damping ring source may be difficult to satisfy. Because there is very little space between the bunches in a train a crossing angle is probably required to avoid parasitic collisions on either side of the interaction point and round beams are very intolerant of a non zero crossing angle.

Flat Beams

The evolution of the concept of a TeV linear collider for a TLC at SLAC includes:

1. Damping rings that generate flat (instead of round) bunches with 1/10 of the horizontal and 1/1000 the vertical emittance of the SLC damping rings.
2. A series of bunch compressors that reduces the bunch length to less than $100\mu m$,
3. A copper linac with gradients in excess of 100MV/m and frequency greater than 11Ghz.
4. At the final focus very strong small aperture quadrupoles yield $\beta_y \sim 0.08mm$,$\beta_x \sim 25mm$, and a luminosity $l = 10^{34}cm^{-2}s^{-1}$.

We would like to consider the substitution of an s-band superconducting linac for the room temperature structure. But first of all we summarize the characteristics of the source and final focus and the relative merit of flat beams.

Source

A damping ring design for a TLC has been completed by Raubenheimer et. al.[6] . The damping ring described by the authors has a circumference of 155m and operates at an energy of 1.8GeV. The damping times obtained with the help of over 20m of 22KG wigglers are 2.5ms and 4.0ms in the horizontal and vertical planes respectively. The beam is stored in trains of ten bunches and there are ten such trains in the ring. The spacing of the bunches within each train is abut 20cm and the trains are separated by 15m. The bunch trains are extracted by a kicker at 360Hz for injection into the linac and then accelerated by a single RF pulse. The kicker is required to rise during the time between passages of the trains, remain powered for the duration of the passage of the trains and then turn off in 50ns, at which time the next bunch train comes by. The tolerance on the flat top of the kicker is very stringent at a level of a few parts in 10^4. The average bunch repitition rate in the linac is 3.6kHz. The turbulent bunch lengthening threshold in the ring corresponds to 2×10^{10} particles in each bunch. The beams in the damping ring are flat so alignment tolerances of the magnetic elements are severe and transverse coupling must be carefully corrected. The horizontal to vertical emittance ratio is 100:1 and the normalized horizontal emittance is $\gamma\epsilon_x = 2.75 \times 10^{-6} m - rad$.

FINAL FOCUS

The beam-beam limit in a linear collider is associated with the beamstrahlung induced energy spread and the disruption of one beam by the other. The luminosity of the collider is given by

$$L = \frac{N^2 b f H_D}{4\pi R \sigma_y^2} \tag{2}$$

where N is the number of particles per bunch, b the number of bunches per train and f the RF repitition rate. The ratio of horizontal to vertical beam size at the interaction point $R = \sigma_x/\sigma_y$. H_D is an enhancement factor due to the pinch effect. The vertical disruption, a measure of the focusing effect of one beam on the other is given by[7]

$$D_y = \frac{2r_0 N \sigma_z}{(1+R)\gamma\sigma_y^2}. \tag{3}$$

r_0 is the classical radius of the electron and σ_z the bunch length. Substitution of (3) into (2) yields

$$L = D_y \frac{N(1+R)\gamma b f H_d}{2r_0\sigma_z R}. \tag{4}$$

For round beams $R = 1$ and

$$L_{round} = 2D_y \left(\frac{N\gamma b f H_D}{2r_0\sigma_z}\right), \tag{5}$$

while for flat beams ($R \gg 1$),

$$L_{flat} = D_y \left(\frac{N\gamma b f H_D}{2r_0\sigma_z}\right), \tag{6}$$

For the same disruption round beams yield twice the luminosity of flat beams.

The consequences of the beamstrahlung imposed beam-beam limit are somewhat different. There is an effective center of mass energy spread induced as a result of the radiation of photons by particles in one beam as they pass through the magnetic field generated by the opposing beam. That energy spread is given in a classical limit by[7]

$$\delta = \frac{r_0^3 N^2 \gamma}{\sigma_z \sigma_y^2} \left(\frac{2}{1+R}\right)^2. \tag{7}$$

In the round beam limit

$$\delta_{round} \rightarrow \left(\frac{r_0^3\gamma}{\sigma_z}\right) \frac{N^2}{\sigma_y^2} \propto L, \tag{8}$$

and for a given energy spread there a strict limit on the luminosity per bunch. In the case of flat beams

$$\delta_{flat} \rightarrow \left(\frac{r_0^3\gamma}{\sigma_z}\right)\frac{4N^2}{\sigma_x^2} \tag{9}$$

The energy spread can be reduced by enhancing the width of the beam even while preserving its area($\sigma_x\sigma_y$). Flat beams also have the advantage that crossing angles can be employed without significant degradation of the luminosity. Finally it is much easier to attain low β^* in one, rather than two dimensions.

The focusing parameters for a TLC flat beam design are $\beta_x \sim 20mm$, and $\beta_y \sim 0.1mm$.[8] In order to attain adequate momentum bandwidth and strong focusing, small aperture quadrupoles are required. In typical designs the acceptable energy spread for the high energy beam as it enters the final focus is less than 0.2%. The quadrupole aperture is insufficient to transport the disrupted opposing beam. A crossing angle is used to provide an alternate extraction path for the exiting beam. The degradation in luminosity due to the crossing angle is limited by relying on a relatively large β_x, a short bunch ($\sim 0.1mm$), and implementing crab-wise crossings. The crossing angle also eliminates parasitic collisions of the closely spaced bunches everywhere but at the interaction point.

BEAM STABILITY

The stability of the superconducting linac depends on the parameters of the beam. To complete the excercise of substituting the superconducting linac for the high frequency copper structure we choose TLC beams. Keep in mind that there are designs for damping rings and a final focus consistent with this choice of beam parameters that yield a luminosity of about $L \sim 10^{34}cm^{-2}s^{-1}$.[8] The linac is required only to deliver 0.5TeV beams with a fraction of a per cent energy spread and without significantly increasing the transverse emittance. Therefore we consider the suitability of an s-band superconducting linac, with an effective gradient of 40MV/m to accelerate beams with:

1. Number of electrons or positrons per bunch $N \sim 2 \times 10^{10}$
2. Normalized emittances $\gamma\epsilon_x \sim 2.75 \times 10^{-6} m - rad$, and $\gamma\epsilon_y \sim 2.75 \times 10^{-8} m - rad$.
3. Bunch length $\sigma_z \sim 0.1mm$.
4. Average bunch repitition rate 3600Hz.

There are two distinct mechanisms in which the quality of the beam can be degraded in the linear accelerator. Short range wakefields lead to transverse emittance growth and energy spread. Wakes associated with high Q resonant modes can destabilize a train of bunches. It has been demonstrated at the SLC that bunches of the appropriate charge can be accelerated with tolerable emittance growth in an s-band structure. Whereas the emittances we are proposing are somewhat smaller, so is the bunch length, and the wakes scale inversely with the length. Longitudinal wakes tend to become more severe with short bunches. It has been shown that with attention to the phasing of the accelerating field with respect to the bunch passage time that the energy spread can be limited to the 0.1% level in a 17Ghz structure.[2] In so far as the longitudinal wake scales inversely with the square of the iris radius, energy spreads are expected to be significantly less problematic at 3Ghz. We are left with a consideration of the effects of higher order cavity modes that destabilize a bunch train.

Multiple Bunch Transverse 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. 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. The coupling of the beam power into a resonant mode is determined by the mode shunt impedance or R/Q. The frequency and impedance of the 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.

In a computer simulation[9] a train of bunches is tracked through a length of RF cavities with total fundamental voltage of 1 TeV (about 25km at 40MV/m). 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 .[10]

$$\Delta \mathbf{E}_{\perp}(t) = q\left(\frac{R}{Q}\right)\frac{c}{2}\frac{\mathbf{x}}{a^2}\sin\omega_n t\; e^{-\omega_n t/2Q_n}. \tag{10}$$

$\mathbf{x}$ 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 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. 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 $(x, x') \rightarrow (x, x' + \Delta x')$. The trajectory at the next cavity in line is given by a phase space rotation.

In a perfectly aligned accelerating structure into which bunches are injected exactly on axis there is no transverse wake. In the simulation, a finite amplitude is introduced into the transverse phase space at the injection point. The source of the transverse displacement is presumed to be jitter associated with the injection kicker that steers the low energy bunch train onto the axis of the linac. Fixed misalignments are amenable to diagnosis and correction while kicker jitter is not. The bunch is treated as a macroparticle so there is no emittance associated with the individual bunch. The growth in transverse phase space is identified as the ratio of the normalized beam size at the final linac energy and at the injection energy,

$$R_{f/i} = \sqrt{\frac{\epsilon_n(E_{final})}{\epsilon_n(E_{initial})}}. \tag{11}$$

In the absence of wakefields the ratio (11)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.

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,[11] which are typical for 4 and 5 cell structures.[12] There are approximately 20 transverse modes with frequencies below the beam tube cutoff. 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 R/Q and Q of the strongest coupling mode are $1.3 \times 10^6 \Omega/m^3$ and 4×10^3 respectively. The stability $R_{f/i}$ is computed as a function of the bunch charge, bunch spacing, and the mode frequency spread. The spread is defined by a gaussian distribution of frequencies of fractional width $\Delta f/f$. There are 100 bunches in the train.

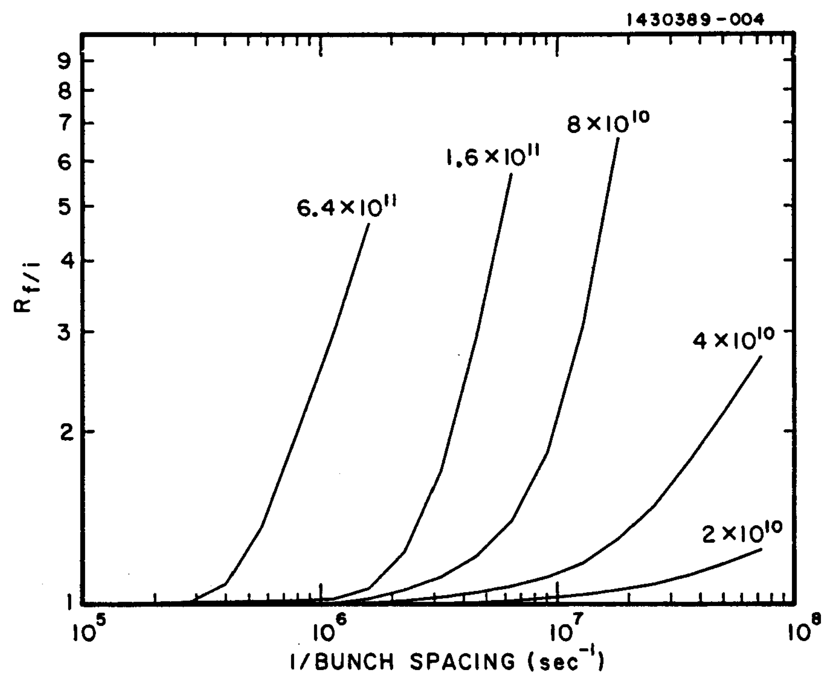

Fig. 1. The ratio $R_{f/i}$ is shown as a function of the inverse bunch spacing for several values of the charge. The mode bandwidth is $\Delta f/f = 2 \times 10^{-5}$. There are 10 distinct modes in each cavity.

It is clear from Fig. 1 that a beam of bunches with $\sim 2 \times 10^{10}$ 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. 1, 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 optimum number of cells per higher order mode coupler will be greater than five.

Wakefield Induced Energy Spread

As noted above longitudinal wakefields induce an energy spread within each bunch and from one bunch to the next. The longitudinal field associated with the long range wake is a superposition of the fields of all of the high Q cavity modes. In its passage through a cavity each bunch sees the voltage induced by all preceeding bunches and as a result each bunch gains a different energy. The beam itself has an energy spread. Each bunch adds an increment of field to each higher order longitudinal mode:[10]

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

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. A similar calculation based on the 10 strongest coupling modes as measured in the 1.5GHz 5-cell and scaled to 3GHz ($\frac{R}{Q}_{max} = 592\Omega/m, with Q_{ext} = 700$) indicates that the bunch to bunch energy spread is negligibly small compared to the intrabunch spread due to the short range wake. For a bunch spacing of $1\mu sec$ the energy spread within the bunch train is only 3×10^{-7}. Apparently an order of magnitude less damping is required in the longitudinal modes than has been attained in the measured cavity.

The effects of the short range wake are significant because of the short bunch length. The loss parameter is computed using BCI[13] to be $k_{loss} \sim 5.4V/pc/cell$ for a $150\mu m$ bunch in a 3GHz structure with an iris radius of 1.7cm. If we consider the bunch to consist of two superparticles, a head and a tail, and that the effective voltage at the tail differs from that at the head by $q_{head}k_{loss}$, then $\Delta E/E = q_{head}k_{loss}/E_{acc}$ where k_{loss} and E_{acc} are the loss parameter and accelerating gradient per unit length. For an effective gradient of 40MV/m we find that $\Delta E/E \sim 0.5\%$. Perhaps 90% of the spread can be compensated by accelerating the bunch off of the crest of the RF oscillation.[2] Nevertheless, the remaining difference in the energies over the length of the bunch will completely dominate the interbunch effects.

The fate of the energy lost by the beam to longitudinal wakes is of some concern. For TLC beams the higher order mode power is $P_{hom} = k_{loss}q^2 f \sim 2.2W/m$. About 10% of the power is extracted by the higher order mode coupler. The remainder is launched into the accelerating waveguide. Some fraction of the power will be dissipated in the room temperature transition sections and the rest into the helium bath. For comparison, the static heat leak is anticipated to be about 1W/m.

Trapped Modes

The possibility of significantly increasing the number of cells per coupler raises the specter of "trapped modes". A trapped mode has so little energy in the end cells that there is effectively zero coupling into the HOM load. Such modes can have high Q($\sim$ *few* $\times 10^9$) but because the energy is unevenly distributed the R/Q is very low. Since the linac is pulsed, the accumulation of energy even in a very high Q mode is limited. A bunch train of length τ has an effective maximum $Q \sim \omega\tau \sim 7.5\times10^6$ for $\tau \sim 200\mu s$. Simulations indicate that a transverse mode with $R/Q < 1 - 5\times10^4\Omega/m^3$ (or about 1-5% of the mode with the maximum R/Q), is not destabilizing, regardless of its Q_{ext}.

SUPERCONDUCTING LINAC WITH TLC BEAMS

Our superconducting linac is required to accept the TLC bunches from damping rings at an average rate of 3600Hz, and to accelerate them to 0.5TeV/beam. The stability of the linac is apparently assured in a 3GHz structure with impedances typical of superconducting cavity geometries. If the bunches are spaced $1\mu sec$ apart then the loaded Q's can be relaxed by at least one and perhaps two orders of magnitude from what has been acheived in 5-cell structures with end cell couplers.

Pulse Width and Duty Cycle

In order to complete the illustration 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 $R/Q = 1919\Omega/m$. 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. 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 $Q_L = \frac{E_{acc}^2}{(R/Q)P_{beam}} = 3.6 \times 10^6$, where E_{acc} is the accelerating voltage and 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 $P_{peak} = U/\tau_e = \frac{E_{acc}^2}{(R/Q)}\frac{1}{\tau_e} = 168kW/m$.

At the end of each pulse the energy stored in the cavities is dumped. $P_{dumped} = U f_{RF}$ 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 dissipated in the fundamental is computed for $E_{acc} = 40MV/m$, and $Q = 4 \times 10^9$. We guess that about 1/3 of the 2.2W/m of the HOM power described above will be dissipated at low temperature. 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.

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 active length of the machine is $25km$. A TLC linac with gradient of nearly 200MV/m is not quite 6km in length. If gradients of 30-40MV/m [14] [15] can indeed be achieved in superconducting cavities then it may prove a practical alternative to a high gradient copper machine.

Linac Parameters	
Center of Mass Energy	1TeV
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	20kW
Static heat leak at 1.5K	25kW
Refrigerator power	52.2MW
Total wall plug power	98.9MW

SRF Drive Linac

An alternative application that exploits the efficiency of superconducting cavities but does not depend critically on high accelerating gradients is the "two-stage" linear collider.[16] In this scheme, there are two parallel linacs, a low gradient, long wavelength superconducting machine, and a high gradient short wavelength structure. The superconducting cavities operate CW to accelerate a high current bunched beam to an energy of about 3GeV. The beam is transported through a series of transfer structures that resonate at the frequency of the high gradient linac. The energy is then transferred to the main linac. The width of the pulse is determined by the spacing of bunches in the drive linac to be consistent with the fill time of the main linac cavities. Energy is restored to the drive beam via the superconducting cavities and conventional CW klystrons.

If the gradient of the drive linac is E_l then the energy extracted by a train of bunches with total charge eN from the low frequency cavities is $\Delta U_l = eNE_l$. If the energy extracted from the drive beam is transferred with an efficiency η_2 to the main linac then the square of the gradient of the main linac is given by:

$$E_0^2 = \eta_2 \Delta U \omega r' = eNE_l\omega r'\eta_2 = \eta_2\eta_1 E_l^2 \frac{\omega r'}{\omega_l r_l'} \tag{12}$$

ω,r',ω_l,r_l' are the frequency and R/Q per unit length for the main linac and drive linac respectively.η_1 is the efficiency with which the drive bunch extracts energy from the low frequency cavities. Since the lineal R/Q scales with frequency we find that the ratio of the gradients is proportional to the ratio of the linac frequencies. Typical parameters for such a two-stage machine include $E_0 = 80MV/m$ at $29GHz$, and $E_l = 6MV/m$ at $350MHz$.[16] The power dissipated in the walls of the superconducting drive cavities is

$$P_{diss} = \frac{E_l^2}{r_l'Q_l} = \frac{E_0^2\omega_l}{\eta_2\eta_1\omega r'Q_l} \tag{13}$$

where we have used (12) to remove the dependence on E_l. The dissipated power is minimized by keeping the gradient in the main linac low (which of course increases its length) and the ratio of the main and drive linac frequencies high. If $Q_l \sim 5 \times 10^9$ then the refrigerator power required to produce a TeV beam is $\sim 33MW$ where $r' \sim 41k\Omega/m$ and $r_l' \sim 270\Omega/m$. Lower main linac frequencies and higher gradients are precluded by the economics of cooling the drive linac cavities.

We can rearrange (13) to compute the total charge required in the low energy beam to establish the high gradient. We find

$$eN \propto \frac{E_0^2}{eE_l\omega r'\eta_2}.$$

A total charge of $N \sim 6 \times 10^{12}$ electrons is necessary to generate sufficient peak power.[16] (Note that we have systematically neglected effects of attenuation in the fill of the high frequency structure. A more careful calculation is done by Schnell.[16]) The fill time of the main linac is about 11.4ns which corresponds to 4 periods of the drive RF. The charge can thus be distributed into four groups spaced by four low frequency wavelengths. Each group is further distributed in about ten bunches spaced by $\tau \sim \frac{2\pi}{\omega}$ where ω is the frequency of the main linac. The length of the bunches must be no more than about 1mm to assure effective coupling to the mode of the transfer structure with main linac wavelength of about 1cm.

The attractive feature of the superconducting drive linac is the efficient conversion of low frequency RF generated with conventional klystrons to very short high peak power pulses. The efficiency is achieved by maximizing the ratio of the frequency of the main linac to that of the drive linac and by accelerating in the drive linac a very intense beam of short bunches. Note that the frequency and gradient of the main linac are both constrained through their impact on the refrigerator power. The difficulties of the scheme include generating and accelerating the drive beam and stable acceleration of trains of low emittance bunches in the main linac.

Conclusions

Designs for fully superconducting linear colliders are practical if gradients in excess of 30MV/m and $Q \sim 4 \times 10^9$ can be attained. It appears that the final focus for flat beams offers considerable flexibility as compared to that for round beams. Beams that yield $L \sim 10^{34} cm^{-2} s^{-1}$ in the TLC designs can be accelerated intact to high energy in a 3GHz superconducting linac with significantly less mode loading than has been realized in 4 and 5 cell structures. Development of a multicell cavity with a minimum number of couplers per unit length is critical to the cost optimization of a superconducting machine. A superconducting drive linac can in principle form the basis of an efficient high peak power RF source for a short wavelength copper structure, but it may prove quite difficult to generate and transport the intense drive beam.

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