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SUPERCONDUCTING RF FOR DIRECT ACCELERATION IN TeV COLLIDERS

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Abstract

The extensive effort by many of the world's best accelerator personnel which has been required for the commissioning of the SLC shows that pushing the SLC design parameters further will be extraordinarily difficult, if not impossible. Use of parameters which are equal to or less restrictive than those of the SLC, together with large-scale application of superconducting cavity gradients which have been achieved on a small scale, makes a 2 TeV e^+e^- collider worthy of consideration. The low peak power required to fill a high Q cavity and a high ratio of higher order mode damping rate to fundamental power dissipation make a linac using superconducting RF accelerating cavities and periodic bunch trains a potentially viable solution.

Normal Conducting Technology

The technology presently used in the SLC is not economically feasible for scaling to a higher frequency. The principal problem is that the energy stored in the resonators is dissipated at the end of each RF pulse. It is difficult to pass a substantial number of beam bunches through on each RF pulse for the following reason: if the beam bunches are too close together, the transverse wakefields from previous bunch passages tend to build cumulatively, knocking the bunches off the centerline; in addition, avoidance of collisions between wrong pairs of bunches near the interaction point becomes difficult. If the beam bunches are far enough apart to allow the wakefields to damp between bunch passages, the fraction of the stored RF energy absorbed by the cavity walls during the same period of time becomes intolerable. As a result of these considerations, people have been led to consider cavities that operate between 8 and 30 GHz, compared to 2.856 GHz for the SLC. The higher frequencies substantially alleviate the stored energy problem, since the same energy density near the axis can be provided without corresponding energy several centimeters off-axis.

However, the higher frequencies bring their own set of problems. One of these is that the deflection caused by a particular mode in the cavity, per unit length, scales as the fourth power of the frequency for a bunch a fixed number of millimeters in length (one power of frequency arises from the fact that the deflecting force initially climbs almost linearly with time after a particle has passed through the cavity). BNS damping, recently applied in the SLC[1], has the problem that it requires different parts of the bunch to be moved to different regions of phase space, and later moved back to the same region. The degree to which this method has been applied in the SLC appears to be approaching the limit to which it is practical because of nonlinearities. If the different parts of the bunch are moved into too widely separated regions of phase space, compensation for nonlinearities when the bunch parts are brought back together will become impractical.

A second problem associated with the use of higher frequencies is that the dissipation time for the stored energy scales as $f^{-3/2}$, where f is the frequency. Short dissipation times require short filling times to prevent the supplied energy from being absorbed before the cavity ever gets filled. Short filling times require higher peak power to get the same amount of energy into the cavity. The combination of high frequencies (small cavities) and short filling times require large numbers of high peak power sources, which are very expensive.

Superconducting RF CW Linac

Use of a fully superconducting linac operating at 2.856 GHz avoids the problems associated with higher frequencies. If the linac were operated CW, there would be no power dumped between RF pulses. The present state of the art of RF superconductivity provides sufficient higher-order-mode damping ($Q_{ext} \sim 10^4$) so that wakefields from equally spaced beam bunches do not affect each other, and the beam bunches are far enough apart that collisions between wrong pairs are not a concern. The problem is that, although such a linac would be far more economical than a normal conducting one of the same frequency, the cost is still prohibitive. One figure of merit is the ratio of gradient to structure cost per unit length. By raising the gradient and by lowering the cost per unit length, the approach can be made more practical. The present state-of-the-art gradient is 5 MV/m (of active length), but values as high as 31 MV/m have been achieved at S-band in single-cell cavities. In order to keep the dissipation per unit length constant, it would be necessary to increase the Q_o as the square of the gradient.

Gradient-limiting defects are normally localized to small regions, and are therefore subject to being compared to defect-free zones surrounding them. However, Q is likely to be limited by a distributed loss, which makes its study much more difficult. In addition, the desire to increase the Q as the square of the gradient makes the problem particularly onerous.

Pulsed RF Superconducting Linac[2]

Operation of a superconducting RF linac in a pulsed mode obviously reduces the requirement for a high Q_o. However, one immediately asks the question as to why the superconducting linac has any substantial advantage over the normal conducting linac at this point.

One reason is that the Q_o of the fundamental mode is typically 10^5 times that in a copper cavity. This means that the time one can take to fill the cavity, without absorption of all the stored energy, is 10^5 times that of a copper cavity. Since RF power sources and their associated controls, interlocks, and support equipment cost roughly the same amount per source, independently of whether the source is limited by peak power or by average power, and since normal conducting linac power sources are severely peak power limited, changing the limitation from peak power to average power is an important economic advantage.

A second important reason is that the much higher intrinsic Q_o in the superconducting case not only reduces the peak power needed, but also permits the energy to be stored in the cavity for a much longer time. This longer time permits an equally spaced number of beam bunches to be passed through the cavity during one RF pulse with a much greater physical separation between bunches than would be possible for the same number of bunches during the short pulse possible in a normal conducting cavity. This greater separation (1.45 km in the example studied) avoids the problem of wrong bunches colliding near the interaction point.

A third important reason is that the ratio of fundamental mode Q_0 to higher-order-mode Q_L is typically 10^5 in a superconducting cavity and 1 in a normal conducting cavity. This means that multiple equally-spaced beam bunches can be passed through a superconducting cavity during an RF pulse without having the wakefields from one bunch affect its successor. This capability, in turn, means that the RF pulse rate can be much lower than the average bunch rate, thereby greatly lowering the amount of power wasted by dumping stored RF energy at the end of each RF pulse.

What is required to make a pulsed superconducting RF linac practical?

A pulsed superconducting RF linac has all beam dynamics parameters less severe than those in the SLC. The only limitation is economic. It is assumed that a TeV collider is not practical if its costs are appreciably higher than those of the SSC.

With the present state of the art, a 2 TeV center-of-mass superconducting linac would cost significantly more than the SSC. More research and development work is required to bring the costs into line. The prospects that such R&D would be successful in accomplishing this objective are excellent.

One limitation of the gradient in superconducting cavities is thermal defects. A resistive region of typically 50 microns diameter produces heat, which raises the temperature of the surrounding superconductor, thereby causing the superconductor to become normal conducting. Such resistive regions can result either from inclusions in the superconductor or from deposits during processing and handling. One possible improvement in this area can be made by further increasing the thermal conductivity of the superconductor (or underlying substrate, if it is not the same), thereby reducing the temperature rise of the surrounding superconductor for a given amount of power dissipation in the thermal defect. Another possible improvement would be the avoidance of clustered precipitates in the superconductor; these precipitates could be avoided by further refin- ing of the bulk superconductor or by depositing the superconductor on the surface atom by atom. Defects deposited in processing and handling could be reduced by using acids, water, solvents, and gases containing fewer particles and by rinsing particles off the surface more effectively. Thermal defects are amenable to study because their locations can be detected by thermometers on the outside of a cavity. Use of surface analysis instruments in conjunction with the thermometry offers the promise of finding the causes of these defects and of being able to avoid them with a much higher probability than is presently possible.

Another limitation of the gradient in superconducting cavities is field emission. Field emission occurs from small areas with field emission coefficients which are enhanced by factors of 100 to 1000. The field emitted electrons are accelerated by the electric fields in the cavity, and deposit heat when they strike the cavity walls. In sufficient quantity, this heat can cause the superconductor to become normal conducting, thereby generating a propagating normal conducting zone. Field emission is believed to be due principally to adsorbed gases and to small, electrically insulated areas. Geometric enhancements should also be reduced, but the evidence to date shows that they are not the predominant factor in enhancing field emission coefficients. DC measurements on niobium samples at the University of Geneva[3] show that the majority of the surface area will support gradients up to 500 MV/m, far in excess of that permitted by the critical magnetic field of the superconductor. Field emission sites can be reconstructed by unfolding the thermal patterns on the cavity surface caused by electron impact. This, in turn, would permit field emission sites to be studied using surface analytic instruments.

The present unit costs of superconducting linacs are (after correcting for inflation) about six times those assumed in an estimate by Tigner and Padamsee[4]. Half of these costs are associated with RF sources, controls, refrigerator, transfer lines, DC magnets (plus their supplies and controls), and the tunnel and associated buildings. The scale of a 2 TeV collider is 237 times that of the superconducting linacs under construction today (assuming ten times the present gradient), which would bring significant economies of scale. For example, if one uses the usual refrigerator scaling law of watts to the 0.7 to 0.8 power, the unit cost would be reduced a factor of 5 and 3, respectively.

Other areas for possible significant cost savings include use of deposited surfaces which reduce the amount of expensive superconductor used. A more careful balancing of parts count against material usage and stored energy (i.e., choice of frequency) could yield savings. If a way were found to avoid "trapped modes" in the cavities, more cells could be used per cavity, thereby reducing the number of separate cavities. Cryogenic RF coupling manifolds, which contain intermediate amounts of stored RF energy, could be used to interconnect cavities, thereby reducing the number of cryogenic penetrations and the number of control circuits. Cryostat designs could be improved to reduce their capital cost and the assembly cost.

The cost optimization procedure used[2] assumed one bunch per damping ring; if this number can be increased without damaging the emittance of the bunches being damped or encountering multi-bunch instabilities, costs would be reduced.

In addition to the total cost, the construction time of the accelerator is a matter of concern, since major accelerator construction projects now are typically spread over 8 or more years. A 2 TeV linear collider could begin operating at twice the LEP-II energy when only 20% completed. This would yield useful physics, and the linear nature of the accelerator would permit construction to continue simultaneously with operation with minimal interference. New sections of accelerator would periodically be connected to existing sections.

Conclusion

Superconducting radio frequency is one of the most promising technologies for construction of a TeV e^+e^- collider. At the present time, the amount of R&D work in progress in the world is much smaller than that which would be commensurate with the promise of the technology and its importance to the continued viability of high energy physics.

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