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SOME ASPECTS OF SUPERCONDUCTING ACCELERATOR DESIGN*

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Abstract

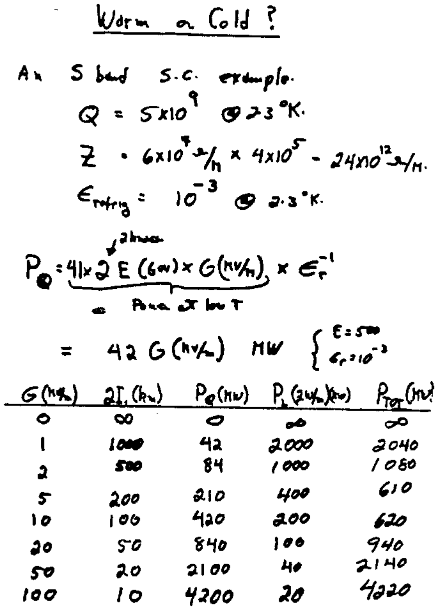
The performance of an accelerator can be characterized by the efficiency with which electrical energy, ac and rf, is converted into accelerating energy, the minimum energy needed to generate a given beam voltage. The current accelerator improvement program at SLAC aims at raising the beam voltage to 50GV which will use 240 klystrons each capable of producing a pulse 5µs in length at a peak power of 36MW. The Linear Collider requires 50MW klystrons to achieve 60GV which will raise the concomittant power consumption to 32.3MW. We show that with superconducting elements we can increase the rf and ac conversion efficiencies and achieve the necessary 60GV using only 1/3 of the present power requirements, provided that we exclude CW operation. We will further demonstrate that this increase in efficiency is crucial and highly significant in the design of a proposed 1000GV linear accelerator.

Introduction.

Energy is dissipated when an electromagnetic field is maintained in an accelerating section. By reducing the temperature of the section we reduce this loss, but the power necessary for the refrigerator increases the ac power into the system. The balance between the power requirements is described by two constants: the improvement factor I_f, which is the ratio of the conductivity of the cooled component and the conductivity of copper at 300K and the refrigeration factor R_f, which is the ratio of the ac power input to the refrigerator and the power dissipated in the component. Thus I_f determines the increase in rf efficiency, and I_f/R_f describes the change in the ac efficiency.

Some fifteen years ago superconducting continuous wave (CW) linear accelerating structures were proposed in order to improve the conversion efficiency. To support a duty cycle change from 0.001 to 1 at the same gradient and ac power input, an I_f/R_f ratio of 1000 is needed. Because with decreasing temperature I_f increases faster in a superconducting system than R_f, we are forced to operate at a temperature where the theoretical quality factor Q approaches the residual Q, which in turn effectively limits the increase in I_f. It is apparently a canonical law of rf superconductivity that high electrical fields, CW operation and a large I_f/R_f ratio cannot be satisfied simultaneously. Very careful surface preparation will yield a high Q under CW conditions but only below fields of 5MV/m.

During the 1982 Summer School on High Energy Particle Accelerators held at SLAC Richter[1] presented the viewgraph shown in Fig. 1 which listed the power required to drive a 1000GV superconducting linac operating at 2.3K in the CW mode as a function of the voltage gradient. Evidently high gradient superconducting accelerators operating in the CW mode are not practical. We demonstrate that in the pulsed mode superconductivity can effect substantial power savings. There is a limit to the pulse energy that can be dissipated in a superconductor and that limit depends on the average power, the heat transfer characteristics and defects in the superconductor.



Warm or Cold ?

An S band s.c. example.

$$Q = 5\times10^{9} \ @\ 2.3\,^{\circ}K.$$

$$Z \cdot 6\times10^{4}\,\Omega/m \times 4\times10^{5} - 24\times10^{12}\,\Omega/m.$$

$$\epsilon_{refrig} : 10^{-3} \ @\ 2.3\,^{\circ}K.$$

$$P_{@} = \underbrace{41\times \overset{2\ linacs}{2}\, E\,(GeV)\times G\,(MV/m)}_{=\ Power\ at\ low\ T} \times \epsilon_r^{-1}$$

$$= 42\, G\,(MV/m)\ MW \quad \begin{cases} E = 500 \\ \epsilon_r = 10^{-3} \end{cases}$$

G(MV/m)	$2L_1$(km)	$P_{@}$(MW)	P_L(2W/m)(kW)	P_{TOT}(MW)
0	∞	0	∞	∞
1	1000	42	2000	2040
2	500	84	1000	1080
5	200	210	400	610
10	100	420	200	620
20	50	840	100	940
50	20	2100	40	2140
100	10	4200	20	4220

Fig.1. Power requirement of a CW/SW 1000GV linac.

Recent experiments at SLAC have confirmed this: as the amplitude of a power pulse incident on a optimally coupled niobium cavity increases, the time at which breakdown occurs increases in such a manner as to maintain constant the energy dissipated per pulse in the cavity. The initial breakdown takes place before the lagging edge of the input pulse reaches the cavity. Thereafter with decreasing power the cavity breaks down during discharge, that is, past the lagging edge of the pulse and after the fields pass their peak values. Fig. 2 illustrates this behavior. A decrease in the pulse repetition rate results in the same behavior, but with a foreshortened time scale. When the pulse repetition rate is further reduced to about one pulse per second at higher power levels the breakdown time varies in an indeterminate manner.

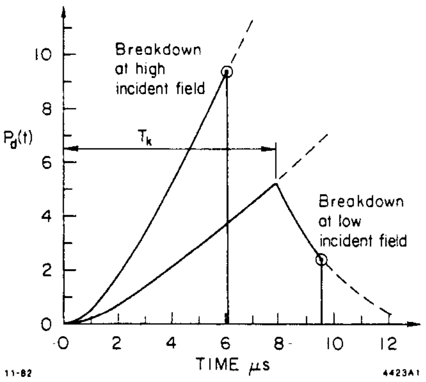


Fig.2. Power dissipated vs time. Areas under the curves represent dissipated energy per pulse, and are equal.

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Specification of Alternate Systems

We have considered the following 4 possible applications of superconducting elements in an accelerator:

1. CW mode with a standing wave section
2. Pulsed mode with a traveling wave section
3. Pulsed mode with a standing wave section
4. Discrete energy storage cavities

An accelerating section is characterized by a number of universal, experimentaly determined parameters, which are interrelated. Its structure parameter is

$$k_s = E^2/(dU/dz) \tag{1}$$

where E is the accelerating electric field at a point z along the section and dU/dz is the corresponding linear energy density. The voltage V, gained by a charged particle traversing a section of length L determines its average gradient, $E_a = V/L$. The accelerating energy, U_s, required by a section to yield a given voltage at a given gradient is

$$U_s = VE_a/k_s = E_a^2L/k_s = V^2/k_sL \tag{2}$$

If η_{rf} and η_{ac} are two dimensionless constants of a given system, call them efficiencies, which determine respectively the rf and ac energies required by a section to yield a given beam voltage at a given average gradient, then we can write

$$\eta_{rf} = U_s/U_{rf} \tag{3}$$

$$\eta_{ac} = U_s/U_{ac} \tag{4}$$

so that

$$\eta_{ac}/\eta_{rf} = U_{rf}/U_{ac} = \eta_{ar} \tag{5}$$

At a pulse repetition frequency N, the rf and ac power requirements of the section are

$$P_{rf} = U_{rf}N \quad \text{and} \quad P_{ac} = U_{ac}N \tag{6}$$

Efficiency of a Standing Wave (SW) Superconducting Section in the CW Mode.

Fig. 3 illustrates the parameters pertinent to the conversion of ac power to accelerating energy characteristic of a system, operating in the CW mode, which includes a superconducting standing wave section. We note the following relations.

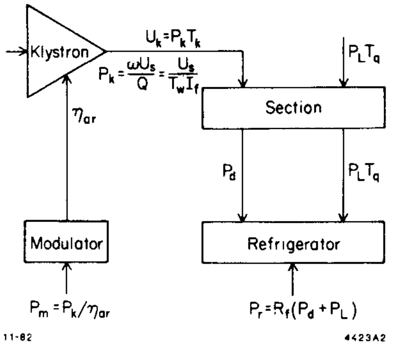

Fig.3. Conversion of ac power to accelerating energy, SW section in the CW mode.

The total ac power is the sum of the power into the modulator, P_m, and the power into the refrigerator, P_r,

$$P_{ac} = P_m + P_r \tag{7}$$

The power dissipated by the section must be equal to the power applied to it, or

$$P_k = \omega U_s/Q \tag{8}$$

where Q is the quality factor of the structure and ω is the angular frequency of the rf power.

Let

$$T_w = Q/\omega \tag{9}$$

when the section is warm. When the section is cold Eq.(8) becomes

$$P_k = U_s/T_wI_f = E_a^2L/k_sT_wI_f \tag{10}$$

The rf efficiency can now be obtained from Eqs. (3) and (10) as

$$\eta_{rf} = (T_w/T_q)I_f \tag{11}$$

where T_q is the time between particle bunches. The power into the modulator is

$$P_m = P_k/\eta_{ar} = U_s/T_wI_f\eta_{ar} \tag{12}$$

The refrigerator must absorb both the power dissipated in the section due to the accelerating process and the power input from the environment, P_L

$$P_r = R_fU_s/T_wI_f + R_fP_L \tag{13}$$

which leads to the reciprocal of the ac efficiency

$$\frac{1}{\eta_{ac}} = \frac{T_q}{T_wI_f\eta_{ar}} + \frac{R_fT_q}{I_fT_w} + \frac{R_f(P_L/L)T_qk_s}{E_a^2} \tag{14}$$

This is a rather artificial definition of η_{ac} inasmuch as it becomes infinite for a CW beam. The reason is that as the time between pulses approaches zero the amount of energy supplied per pulse to maintan U_s also approaches zero. However as T_q increases, a point is reached where it costs more to store energy from one bunch to the next than to discard and regenerate it by the time the next bunch comes along. Under such conditions, a pulsed structure is clearly indicated.

The power input into a CW section is independent of the electron bunch traversal frequency. Let us not forget that energy is dissipated not only when a bunch passes, that is when the field is put to use, but also when the field idles. The magnitude of this effect is best illustrated by the SLAC accelerator which has an active length of 2880m. Suppose we wish to maintain an accelerating gradient of 20.9MV/m and operate the accelerator at 2.3K where I_f = 400,000, R_f = 1000 and R_L/L = 2W/m. The power required by such a machine would be 63MW. Such an I_f and gradient can only be achieved simultaneously at a very particular aspect of planets and stars which so far has not taken place. If we raise the temperature to 4.2K we easily achieve an I_f = 4000 and an R_f = 400 but the refrigeration power penalty is then no less than 2.5GW!

In a linac, the length of the machine and the power scale linearly with the beam voltage at constant gradient. Thus an accelerator designed to produce a 1000GV beam would consume 1GW of power even if it were maintained at 2.3K. Obviously we cannot afford to keep an accelerator filled with energy continuously.

Efficiency of a Traveling Wave Section (TW) In the Single Bunch (SB) Mode

The conversion of ac to accelerating energy in a superconducting TW section operating in the SB mode is illustrated in Fig. 4. The SB mode is a pulsed mode where the klystron pulse length equals the section filling time.

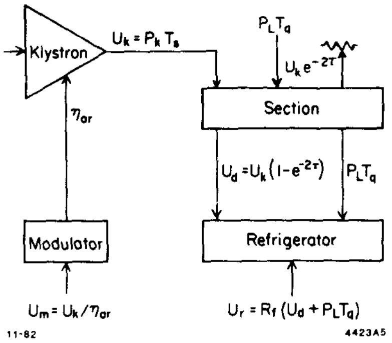

Fig.4. Conversion of ac power to accelerating energy, TW section in the SB mode.

The transmitted power as a function of distance along the section is[2]

$$P = P_k \exp(-\omega z/Q v_g) \tag{15}$$

where P_k is the klystron peak power and v_g is the group velocity along the section. The linear energy density equals the ratio of power transmitted, P, to the group velocity .

$$dU/dz = P/v_g$$

From Eq. 1 we obtain $E^2 = k_s\, dU/dz = k_s P/v_g$

so that $V = \int_0^L E dz = (P_k k_s/v_g)^{1/2} \int_0^L \exp(-\omega z/2Q v_g) dz$

and $V^2 = k_s P_k T_s L (1-e^{-\tau})^2/\tau^2$

where τ is the section attenuation, and is related to the section filling time, $T_s = L/v_g$, by

$$2\tau = \omega L/Q v_g = T_s/T_w I_f \tag{16}$$

From the definition of rf efficiency, we obtain

$$\eta_{rf} = [(1 - e^{-\tau})/\tau]^2 \tag{17}$$

If τ is very small as is the case in a superconducting section then

$$\eta_{rf} = (1-\tau) = 1 - T_s/2T_w I_f \tag{18}$$

The klystron peak power which is independent of L and T_s is

$$P_k = E_a^2 v_g/k_s \eta_{rf} \tag{18a}$$

The energy dissipated in the section is

$$U_d = U_s/\eta_{rf}\,(1 - e^{-2\tau}) \tag{19}$$

Again $\tau \ll 1$ so that by virtue of (17) and (19)

$$U_d = U_s/\eta_{rf} \times T_s/T_w \times 1/I_f \tag{20}$$

Likewise from Fig. 4, the required refrigeration and modulator energies are respectively

$$U_r = (R_f/I_f)(U_s/\eta_{rf})(T_s/T_w) + R_f P_L T_q$$

and $$U_m = U_s/\eta_{ar}\eta_{rf}$$

The total ac energy required is $U_{ac} = U_m + U_r$

which yields the reciprocal of ac efficiency

$$\frac{1}{\eta_{ac}} = \frac{1}{\eta_{ar}\eta_{rf}} + \frac{R_f T_s}{I_f T_w \eta_{rf}} + \frac{R_f (P_L/L) T_q k_s}{E_a^2} \tag{21}$$

We note that in a TW section the required pulse length is reduced by the factor $1-v_g/c$ because the energy travels with the bunch and therefore the section does not have to be completely filled when the bunch arrives. Generally this factor is almost unity because $v_g/c \ll 1$. It is only important when the group velocity is a significant fraction of the particle velocity. Both the modulator and refrigerator energies are reduced by it. Thus, both the rf and ac efficiencies are increased by $1/(1-v_g/c)$. This factor indicates how well the energy is concentrated where the particle is in longitudinal space just as k_s indicates how well the energy is concentrated in transverse space.

Efficiency of a Standing Wave Section In the Single Bunch Mode

When it is operating in the SB mode a SW section resembles a TW section; in either case we reject the stored energy once it has been used by the particle bunch. As in a TW section, if the filling time is too long it will not fill completely, if too short, it will overfill. In a such a section Q_e determines the filling time in the same way the group velocity does in a TW section. The filling time in the former is determined by the degree of coupling between it and the outside world while in the latter it is the degree of coupling between cavities. With short pulse lengths Q_e is low which not only reduces tuning problems, but also helps in removing from the section the harmonic power induced by the bunch.

The expressions for the rf efficiency, the peak power and the energy dissipated during a pulse has been derived by Farkas[3], and evaluates for an optimized system as

$$\eta_{rf} = 0.814(1-0.4T_s/T_w I_f)$$
$$P_k = E_a^2 L_s/T_s k_s \eta_{rf} \tag{22}$$
$$U_d = 0.846 U_s T_s/T_w I_f$$

where T_s is the loaded cavity time constant.

The energy input to the refrigerator is $R_f U_d$ so that

$$U_r = 0.846\, U_s (R_f/I_f)(T_s/T_w) \tag{23}$$

Combining Eqs. (3)(22) and (23) we obtain the reciprocal ac efficiency:

$$\frac{1}{\eta_{ac}} = \frac{1}{\eta_{ar}\eta_{rf}} + 0.846\frac{R_f T_s}{I_f T_w} + \frac{R_f (P_L/L) T_q k_s}{E_a^2} \tag{24}$$

Note that this expression for $1/\eta_{ac}$ is almost identical to Eq. (21). The difference arises because in the SW case the power multiplication is due to reflections from the end of the section rather than due to local reflections in single cavities as in the TW case.

Discrete Energy Storage Cavities

We noted above that the power input to the refrigerator is proportional to T_s/T_W. We can make this ratio small and store rf energy in a storage cavity in which no surface electric fields exist, rather than in the accelerating section. Also in a storage cavity T_W can be made much longer than in the accelerating section. The SLAC accelerator has used this scheme successfully for many years.[4]

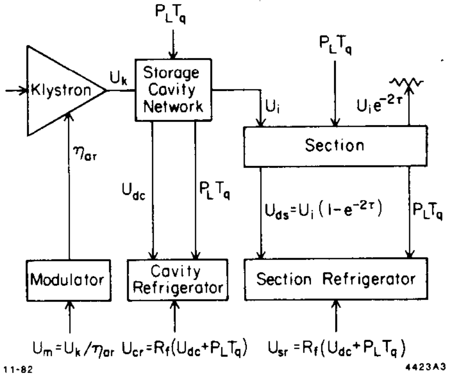

Fig.5. Conversion of ac power to accelerating energy, TW section in the SB mode, and discrete storage cavity.

Fig. 5 illustrates the parameters describing the conversion of ac power to accelerating energy characteristic of a system which includes a discrete storage cavity and a TW section operating in the SB mode. The ac efficiency is

$$\eta_{ac} = (U_s/U_m)/(1+U_{cr}/U_m+U_{sr}/U_m)$$

If the present SLAC copper storage cavities whose $T_W = 5.57\mu s$ were replaced by superconducting cavities the parameters shown in the last line of Table 1 would result. The cavity Q_e, the pulse width and section filling times have been optimized for maximum compression efficiency.

Comparison of a CW/SW Section with a SB/TW Section

The choice of operating mode, pulsed or CW depends simply on whether it costs more to store energy in a section and make it available for subsequent bunches (CW) or to dump the energy and refill the section (pulsed). To determine the time between bunches T_q, where the efficiency of a pulsed system matches and then overtakes the efficiency of a CW system, we equate their respective efficiencies and evaluate T_q. Thus

$$T_q(1/T_WI_f\eta_{ars}+R_f/I_fT_W) = 1/\eta_{art}\eta_{rf} + (R_f/I_f)(T_s/T_W)/\eta_{rf}$$

or

$$T_q = \frac{T_W[1/\eta_{art} + (R_f/I_f)(T'/T_W)]}{\eta_{rf}[(1/I_f\eta_{ars}) + R_f/I_f]} \qquad (25)$$

This expression for T_q is true at all temperatures and for all materials. Wilson[5] has made such a comparison in his discussion of room temperature rf systems for large storage rings. However when we deal with a superconducting section we quickly find the several advantages of pulsed mode operation:

(i) As we have seen before, gradients considerably in excess of the current 5MV/m for SW/CW cavities can be attained.

(ii) By virtue of the discarded energy the heating of the section by the power dissipated is reduced by the duty cycle. A local hot spot therefore has time to cool between pulses which may reduce the rate of catastrophic breakdown. Such time dependent phenomena explain our measured peak electric fields in excess of 52MV/m in a TM_{010} cavity at 4.2K without significant deterioration of Q_0[6].

(iii) The structure can operate at 4.2K where the residual Q is greater than the BCS Q. In our tests at 4.2K we never observed the effect of the residual Q, not even with cavities that received no elaborate preparatory surface treatment.

(iv) No special tuning problems are encountered because the loaded Q is low, nor is there a need for an additional coupler to remove the harmonic power generated by the bunch.

(v) We can devise means to reduce U_s by choosing an appropriate structure and frequency.

(vi) We can decrease the ac and rf average power by decreasing N which however leads to a decrease in luminosity.

Discussion

Table 1 is a summary of the various parameters describing the SLAC accelerator for different stages of energy enhancement, some actual others presented as options to be examined.

The first entry is the benchmark accelerator which uses the existing SLAC sections. This machine will yield 60GV for an investment of 29MW of power when we compress the 5µs pulse to 0.82µs. The second entry uses a klystron whose pulse length equals the section filling time. Development of such a klystron would improve the rf efficiency but the ac efficiency would remain unaffected due to switching losses. Moreover the peak voltage is high.

A CW superconducting structure with an as yet unattained I_f of 400,000 at 20.9 MW/m requires double the power as shown by the third line. The fourth line, a superconducting TW/SB option using a SLAC section, at 4.2K with an R_f of 400, an improvement factor of 4000, a structure parameter of 76.4TΩ/msec, and a T_W of 0.917µs. The ac power required is now reduced by a factor of 2.5. The reason? We have eliminated the losses in the structure and the need for and hence the losses inherent in pulse compression. If we now increase the pulse length to 20µs we decrease the ac efficiency (Line 5) but the amount of ac power required is still only about one half of the non-superconducting case. Effectively we have maintained the accelerating gradient, decreased the peak power per unit length which determines the number of sources required but paid for it with a decrease in the ac efficiency.

In the sixth option we take advantage of Wilson's[7] design, namely that the accelerating energy and hence the rf and ac energies decrease as the square of the frequency. While the efficiency do not greatly change the power requirements are substantially less.

The last entry in the table illustrates what would happen if we replaced the present copper storage cavities whose $T_W = 5.57\mu s$ with superconducting cavities. We have optimized the cavity Q_e, the pulse width and section filling times to give the maximum compression efficiency. This technique is useful only for long rf pulses.

The refrigeration powers listed in the table would be reduced by a factor of three without the need for an increase in the improvement factor if Nb_3Sn sections are used at 12K.

The power requirements given in the table are for a 60GV accelerator. A 1000GV machine with a 20.9MV/m gradient would be 48km long and its power requirements can be obtained from the table by multiplying the appropriate entries by 16.7.

System	T_s μs	T_k μs	L_s m	η_{rf}	η_{ac}	P_k MW	P_m kW	P_r kW	P_{ac} kW	P_{tot} MW
1. Existing	0.82	5.00	3.00	.311	.103	11.1	30.0	-	30.0	28.8
2. T_k=T_s	0.82	0.82	3.00	.597	.107	35.0	28.7	-	28.7	27.7
3. CW/SW	-	-	3.00	51.8	.047	60w	0.10	65.6	65.7	61.8
4. TW/SB	5.00	5.00	12.0	1.00	.266	13.7	37.2	9.24	46.4	11.1
5. TW/SB	20.0	20.0	96.0	1.00	.172	27.4	261	313	573	17.2
6. TW/SB	3.20	3.20	96.0	1.00	.211	55.6	106	64.6	171	5.31
7. Storage Cavity	6.00	20.0	28.8	.818	.229	10.1	95.4	33.5	129	12.9

Table 1. The parameters of a 60GV superconducting accelerator with E_a = 20.9MV/m at 180pps. The attenuation in the wave guide feeds has been neglected.

How to Beat the Second Law of Thermodynamics: Bunch Recirculation

In a superconducting TW structure the rf energy loss is essentially zero and therefore we can afford long filling times. This condition, together with light bunch loading ensures that almost all the input rf energy is available at the output end of the section. The left-over energy can be recycled to drive a second, parallel accelerator. We recognize three possible modes of operation:

(i) A second bunch is injected a filling time later into the second accelerator

(ii) The original bunch is returned to the input end and injected into the second accelerator. The filling time must equal the roundtrip time of the bunch as illustrated in Fig. 6. We do not need a second accelerator if we use high power rf switches.

(iii) The original bunch is injected into the second accelerator but in the opposite direction. This requires the filling times of successive sections to decrease. The target and the injector are at the same end as illustrated in the bottom part of Fig. 6.

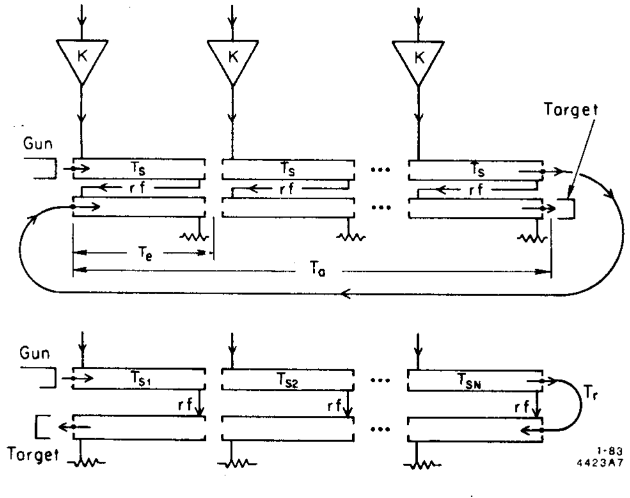

Fig. 6. Double pass recirculation scheme.

Recirculation for the same beam voltage reduces rf energy by a factor of 4. The refrigerator power is doubled under our assumtions, but as it is a small fraction of the modulator power, the net increase in ac power is small.

A Design for SLAC

In the SC/SB mode we can achieve 60GV with the present klystrons: we preserve the present 3m section length and connect 8 sections in tandem so that the section length is 24m. Since the pulse length is 5μs, the group velocity is 4.8m/μs, 30% greater than the present average group velocity of 3.66μs/m, and 2.5 times greater than the present minimum group velocity, so that the higher order mode loss factor is smaller. Equation 18a gives the klystron peak power as 27MW.

One pair of modulator, 50MW klystron stations, each consuming 135KW ac power is replaced with one modulator, 27MW klystron station requiring 74kW together with a 60W refrigerator using about 24kW of ac power. The capacitors of the superfluous modulator can be added to the principal modulator in order to double its pulse length. Further we can opt for either 120 refrigerators at 60W each or 30 units at 240W each. In either case the theoretical refrigeration power needs are 2.9MW. To this we add 8.9MW of ac modulator power and obtain a total power requirement of 11.8MW which must be compared to the 32.3MW consumed by a 50MW klystron system, a net saving of 20MW. Here as in Table 1 we neglect the attenuation of the waveguide network, since it operates near liquid nitrogen temperature.

A alternate design is 3 stations per sector, 32m section length, 6.4m/μs group velocity and 36MW peak power.

The superconducting mode further allows a fourfold decrease in rf and ac powers at 60GV or an increase in beam voltage to 120GV without increasing rf power, via recirculation. If in addition we develop and install 50MW klystrons the beam voltage will increase to 150GV, provided the sections can sustain a gradient of 27MV/m.

So far we have discussed only SB operation. If we wish to retain the long pulse (LP) mode we can also do so with a superconducting linac in which the sections are 3m long and the klystron power is distributed as in the present normal machine. The section would have a constant group velocity of 3.66m/μs, a filling time of 0.82μs, and a beam pulse width of 4.4μs. With 36MW klystrons the beam voltage increases from 28.8GV to 40GV and with 50MW klystrons the beam voltage increases from 33.9GV to 47.5GV.

Cooling in the LP mode is equivalent to stage 1½, but without doubling the ac and rf powers.

Further Improvements.

So far we assumed a niobium disk loaded waveguide section, with proven parameters. Should niobium-tin coatings on copper substrates prove feasible and should such coatings have the desirable rf properties then we would operate the accelerator at about 12K and thereby reduce the total refrigerator load to 1.6MW. Also if we replace the disk loaded structure with a TE_{111} cavity-like structure[8] which has twice the k_s, the number of stations is reduced from 120 to 60, and the ac power into the modulators is halved to 5.2MW. Thus we can achieve 60GV with 6.8MW of ac power, a saving of 25MW.

Apart from saving 20MW of ac power the choice between a cold and warm accelerator depends on the cost of installation and operation of a multi-unit refrigeration plant, and the development, fabrication and installation of superconducting sections compared to the development, fabrication, installation and maintenance of 240 50MW klystrons together with the necessary modification of the associated modulators.

The superconducting concept is rather conservative: recent experiments at SLAC have proven that the requisite gradient of 20.9MW/m can be sustained readily[6] whereas the feasibility of 50MW stations has yet to be demonstrated. We have routinely obtained peak surface electric fields of 50MW/m in a TM_{010} cavity which had received no prior special treatment, and we believe that we can achieve much higher fields once the field limiting sliding joint coaxial probe used in our tests is replaced. A test with a short niobium TW section in our current test system fed by a 36MW, 5μs klystron would unambiguously reveal the capabilities and limitations of such a superconducting SB/TW accelerator.

There are many advantages inherent in a superconducting section operating in the pulse mode, which collectively argue strongly in its favor. These are:

(1) Higher efficiencies in both the SB and LP modes. There is no need to increase modulator and substation power ratings, to achieve 60GV or more beam voltage.

(2) The new sections can have a higher k_s, and hence require less modulator power. The group velocity is higher and hence the higher order mode loss factor is smaller.

(3) Superconducting sections and 50MW klystrons complement and are not mutually exclusive. Such sections in the single bunch mode can serve as a backup for the 50MW klystron development. They can be used in parallel i.e. both installed in the same sectors, or in series i.e. 36MW, 2.5μs or 5μs klystron and superconducting sections in some sectors, 50MW klystrons in other sectors. Also, single bunch operation of superconducting sections will reduce the 1μs klystron peak and average power requirements by 68%. In a warm section nearly half the rf energy is dissipated in the walls before it had a chance to accelerate the bunch.

(4) The possibility of further reduction of power requirements or to increase the beam voltage via recirculation is inherent in the concept.

(5) A superconducting section or sections serves as a model for larger accelerators.

Conclusion

Surely it does not make any sense to abandon the concept of a high gradient superconducting linear accelerator just because we have so far pursued unsuccessfully the chimaera of the improvement factors of 400,000 needed for CW operation at gradients in excess of 5MV/m. We have the very attractive option of the pulsed mode operation where with modest and readily attainable improvement factors we can more than double the overall efficiency and we can use relatively low peak power, long pulse length klystrons. Using proven technology, we can reach 1000GV with 200MW of ac power at 20.9MW/m gradient and 180pps. If we recirculate we can reduce the ac power to 50MW.

Therefore the answer to Richter's question in Fig. 1, "Warm or cold?" is clearly "Cold, but not too cold"!

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