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A TWO-STAGE RF LINEAR COLLIDER USING A SUPERCONDUCTING DRIVE LINAC

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Abstract

The efficiency from RF input to beam power of a normal conducting travelling-wave linac can be raised above 5% albeit at the price of a very short power pulse and an appreciable but probably correctible energy spread. Compensated multibunch operation may yield 30% efficiency but higher order wakefield problems have to be solved and a suitable final focus system must be found. The worst remaining problem seems to be the economic and efficient generation of peak RF power. The solution proposed here consists of a limited number of CW UHF klystrons, a superconducting UHF drive linac and a tightly bunched drive beam of several GeV average energy, transferring energy from the superconducting linac to the main linac via short sections of transfer structures. The power balance of this scheme is analysed and it is found that overall efficiency can be very high. Very dense drive bunches are required. Present-day performance of superconducting cavities is already sufficient to make the scheme viable at main linac accelerating gradients approaching 100 MV/m.

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1. Introduction

If the classical RF-driven, room-temperature, travelling-wave linac is to be used in a linear collider at accelerating gradients approaching or exceeding 100 MV/m an economic source of peak power has to be found and the average power efficiency from mains input to beam power must be made acceptable. Clearly, to drive a structure with shunt impedance per unit length R' to an average accelerating gradient E_0 the peak power $\hat{P}_L$ per section length L must exceed E_0^2/R'. As this power is enormous the electron linac is always pulsed with a very small duty cycle. On the other hand, as the quality factor Q is much too small to conserve an appreciable fraction of stored energy over a realistic repetition period it is often assumed that the average RF input to one linac is roughly given by

$$\frac{\langle P_b \rangle}{\eta} \tag{1}$$

where $\langle P_b \rangle$ is the average beam power and η the fraction of stored energy extracted by a beam pulse. This fraction cannot be very large, certainly not above 10% if the beam's energy spread - about $\eta/2$ - should remain acceptable or at least correctible.

Dissipation during the fill time will make the efficiency from RF input to beam power worse than η. However, by making the structure fill time very short, the additional efficiency factor can be kept close to unity at the price of a further increase of peak power. This will be described in Section 2. Moreover, it might be possible to push the RF to beam efficiency substantially above 10% at acceptable energy spread by dividing the beam pulse into a train of closely spaced bunches and restoring the energy extracted by each bunch during the bunch interval[1]. This is discussed in Section 3.

A serious problem remaining is the economic generation of peak RF power of the order of two terawatts for a 1+1 TeV collider. The solution proposed and discussed in this paper is to employ a tightly bunched high-energy drive beam running alongside the entire main linac and directly powering it via short, side-coupled transfer cavities. The drive beam receives its energy from superconducting CW linac sections occupying only a fraction of the total length. This drive linac is operated at UHF frequency with an accelerating gradient much below E_0. The drive linac in turn is powered by a limited number of CW klystrons of proven design and the entire scheme may be viewed as one of pulse compression from CW to nanoseconds and harmonic conversion from UHF to microwaves. The power balance of this will be analysed and basic design equations derived in Sections 4 to 10.

The aim of this paper is an overview of basic constraints and effects estimated to be below 10% are generally neglected. The analysis is limited to the fundamental frequencies of the two stages of linear accelerator involved. Higher order wakefields will certainly be serious but are outside the scope of this paper. A 1+1 TeV collider with luminosity of 10^{33} $cm^{-2}s^{-1}$ or more is taken for numerical examples.

2. The main linac

The main accelerating structure is assumed to be composed of classical travelling wave linac sections of length L, group velocity v and shunt impedance per unit length R' operated at frequency $f = \omega/2\pi$ and average accelerating gradient E_0. Constant group velocity is assumed unless stated otherwise. Other structure constants are the quality factor Q, the "R over Q per unit length" r' defined as

$$r' = \frac{R'}{Q} = \frac{E^2(z)}{\omega W'(z)} \tag{2}$$

where W'(z) is the stored energy per unit length z. A related parameter is the attenuation constant α for energy given by

$$\alpha = \frac{\omega L}{Qv} = \frac{L}{z_0} = \frac{\tau}{\tau_D} \tag{3}$$

where z_0 is the attenuation length, τ_D the decay constant for stored energy in an isolated cell and

$$\tau = \frac{L}{v} \tag{4}$$

the group delay or "fill time". Note that if a given structure geometry is scaled to different wavelengths

$$Q \propto \omega^{-\frac{1}{2}}, \quad R' \propto \omega^{\frac{1}{2}}, \quad r' \propto \omega \text{ and } \tau \propto \omega^{-\frac{3}{2}}.$$

Each section is powered by a square power pulse of peak power $\hat{P}_L$ and duration τ so that the wave front progressing in the section just reaches its end when the power is switched off. At this moment the beam pulse is made to pass. In this simple model the wave front is assumed to be sharp and the passage of the beam instantaneous, implying $v \ll c$. In reality the group velocity may well be as large as 0.1 c. In a forward wave structure this would actually permit reducing the duration of the power pulse by 10%, in a backward wave the opposite would be true and for the present analysis it has been ignored.

With all these assumptions and simplifications one finds the peak power per section length as

$$\boxed{\frac{\hat{P}_L}{L} = \frac{E_0^2}{g^2 \alpha R'}} \tag{5}$$

where

$$g = \frac{1 - e^{-\alpha/2}}{\alpha/2} \tag{6}$$

Clearly the total average RF power per linac $\langle P_{RF} \rangle$ equals $\hat{P}_L \tau$ times the total length and repetition rate. With the fraction of stored energy extracted by a charge bNe given by

$$\eta = \frac{bNe\omega r'}{E_0} \tag{7}$$

and the total beam power by

$$\langle P_b \rangle = bNeUf_{rev} \tag{8}$$

(eU being the final particle energy and f_{rev} the repetition rate), the average RF power can be written as

$$\boxed{\langle P_{RF} \rangle = \frac{\langle P_b \rangle}{g^2 \eta}} \tag{9}$$

The total charge bNe may be contained in a single bunch per pulse or in a (small) number b of closely spaced bunches.

The classical choice is for the minimum of peak power occurring at $\alpha = 2.5$ and $[g^{-2}\alpha^{-1}]_{min} = 1.23$. But this implies $g^{-2} = 3.1$ and, hence, an intolerable wastage of average power. Clearly, since average power is of basic importance here a smaller value of α must be chosen, in spite of the concomitant increase of peak power. For all numerical examples in this paper $\alpha = 0.5$ (hence $g^{-2} = 1.28$) will be chosen, implying that the peak power per section length is 2.56 times E_0^2/R'.

In Table 1 three examples of basic parameters are given for 6, 20 and 29 GHz, called cases A, B and C respectively. In all cases the beam power is 5 MW, the top energy (per linac) 1 TeV and the bunch population $N \sim 5.5 \times 10^9$ giving about 10^{33} $sm^{-2}s^{-1}$ luminosity with $\sigma_r^* \sim 80$ nm beam radius and $H \sim 4.5$ enhancement at collision. As the energy extraction per beam pulse is taken as 8% the average RF input per linac equals 80 MW in all three cases, i.e. the RF to beam efficiency is 6.25% The main question here is whether 4% energy spread is, in fact, correctible before the final focus is reached. It will be noted that at 6 GHz the common effort of ten successive bunches of typical population is required to achieve 8% extraction in spite of the very modest assumed gradient of 40 MV/m.

Final focus and beam emittance are not among the subjects of this analysis and the last six lines of Table 1 are added for illustration only. The beam-beam radiation is still essentially in the classical regime and the classical formula has been used. It is true that $\sigma_z = 1$ mm would be a little too long for good energy spread at 29 GHz. Whether a higher luminosity per unit beam power may be achievable by radical reductions of σ_r^* and σ_z (quantum regime) is outside the scope of this paper.

TABLE 1

Main linac parameters for three frequencies. Parameters for one linac.

Case	A	B	C	
Final energy eU	1	1	1	TeV
Frequency f	6	20	29	GHz
Average accelerating gradient E_0	40	40	80	MV/m
Total active length L_{tot}	25	25	12.5	km
Shunt impedance per unit length R'	80	141	170	MΩ/m
Quality factor Q	9500	5030	4150	
R'/Q = r'	8.4	28	41	kΩ/m
Attenuation constant for power α	0.5	0.5	0.5	
Fill time τ	126	20	11.4	ns
Peak power per section length $\hat{P}_L/L$	51.1	29	96	MW/m
Bunch population N	6.3	5.68	5.35	$\times 10^9$
Energy extraction per pulse η	0.08	0.08	0.08	
Number of bunches per pulse	10	1	1	
Repetition rate f_{rev}	0.496	5.5	5.8	kHz
Average RF power $\langle P_{RF} \rangle$	80	80	80	MW
Beam power $\langle P_b \rangle$	5	5	5	MW
Beam radius at collision σ_r^*	90	78.5	77	nm
Disruption D	2.2	1.3	1.3	
Pinch enhancement H	5.5	4.5	4.5	
Beam-beam radiation loss δ	0.13	0.23	0.21	
Bunch length σ_z	2	1	1	mm
Luminosity	1.06	1.03	1.01×10^{33}	$cm^{-2}s^{-1}$

The structure constants assumed are for disc-loaded structures. However, the low group velocity of such structures (about 0.02 c) would lead to inconveniently short section lengths, especially for the higher frequencies (L = 7.4 cm in case C). Thus, suitable structures with stronger cell-to-cell coupling should be developed, taking into account mechanical and thermal problems, tolerances and possible manufacturing methods as well as longitudinal and transverse wakefields. For illustration a pure Jungle Gym structure for case C may be considered as a starting point. It would have about 5 mm diameter. At 3 kW/m average dissipation pairs of π/2 mode loading bars of 0.5 mm diameter (Cu) would reach about 30°C temperature rise.

For the small values of attenuation constant proposed here the use of a constant gradient (graded group velocity) structure changes very little. In equation (5) the factor $g^2\alpha$ in the denominator is replaced by α_0 (the attenuation constant at the input) alone. In equation (9) the factor g^{-2} is replaced by a factor

$$\alpha_0^{-1}\ln(1-\alpha_0)^{-1} \quad .$$

For $\alpha_0 = 0.4$ the average power factor is 1.28 as above and the peak power factor is 2.50 as compared with 2.56. Constant gradient would be advantageous, however close to the breakdown limit, and would assure that the beam loading η does not change the spatial distribution of field (for as long as r' is constant along the graded structure).

In either case (and with $\eta \sim 0.1$) roughly half of the input energy reappears at the output. Instead of dissipating this electrical energy in a load resistor an attempt should be made to recover it. This may be done by reconverting it to d.c. in a rectifying load. Conversion from microwave power to d.c. has in fact been achieved[2)], albeit with a continuous wave, at the level of tens of kilowatts and with about 80% efficiency. A superconducting drive linac offers the possibility of much easier energy recovery, as discussed in Section 10.

3. High efficiency by compensated multibunch operation

In principle, at least, the efficiency of energy transfer to the beam at acceptable energy spread can be increased substantially beyond equation (9) by employing a train of bunches occupying a certain fraction of the fill time τ. The charge of each bunch is limited by the maximum energy extraction η permitted by the concomitant energy spread but the bunch interval τ_b is adjusted so that the fresh influx of RF energy restores the average accelerating field from bunch to bunch[1)]. It would appear that this "compensated multibunch" operation is a very promising scheme deserving detailed study. But since one of the main problems, the influence of higher order wakefields, is outside the scope of this paper anyhow the following analysis has been limited to loss-free wave propagation for simplicity. Dissipation is accounted for by applying the factor g^{-2} of equation (6) at the end. The simple model then is the following.

The first of a train of b bunches passes the structure at time $\chi\tau$ when the propagating wave front is at $\chi L < L$. If eN is the charge of this bunch it induces a decelerating field component ΔE given by

$$\frac{\Delta E}{E_0} = \frac{Ne\omega r'}{2E_0} = \frac{\eta}{2} \tag{11}$$

all over the full section length L. Here E_0 is the RF driven field within χL and η the energy extraction given by equation (7) for b = 1. The particles of this bunch gain an average voltage equal to

$$E_0 L(\chi - \frac{\eta}{4}) \tag{12}$$

To give the second bunch the same voltage the bunch interval τ_b must be chosen so that $\tau_b v E_0 = L\Delta E$ and hence

$$\tau_b = \frac{\eta}{2}\tau \tag{13}$$

The last one of b equidistant and uniformly populated bunches gains

$$E_0[\chi L + (b-1)\tau_b v] - \Delta E[(b - \frac{1}{2})L - \sum_{i=1}^{b-1} i\tau_b v] \tag{14}$$

The last term represents the fractions of beam-induced waves that have already left the structure at that time. If τ_b is adjusted according to equation (13), the last bunch experiences an absolute energy error with respect to the first one of

$$LE_0 \frac{\eta^2 b(b-1)}{8} \tag{15}$$

It should be noted that, although η is the actual fraction of energy extracted by one bunch, the concomitant energy spread is $\eta/2\chi$ (for small η) since the RF driven field stretches over χL only while the charge-induced field stretches over the full length L. For this reason an equivalent energy extraction

$$\eta_\Delta = \frac{\eta}{\chi} \tag{16}$$

[with η given by equation (7) for b = 1] is introduced as the parameter whose choice, 10% say, is governed by energy spread. Using this and equation (12) the fractional energy error of the last bunch with respect to the first one equals

$$\chi \frac{\eta_\Delta^2 b(b-1)}{8\left(1 - \frac{\eta_\Delta}{4}\right)} \tag{17}$$

While the restriction to equidistant uniformly populated bunches may be unnecessary it appears prudent for the moment to restrict expression (17) to a few percent.

A good choice of filling factor χ may be 0.8 implying that 20% final energy of a given linac is sacrificed in order to gain luminosity for given RF power. Since the last bunch passage should coincide with the end of the fill time τ

$$b - 1 = 2\,\frac{1-\chi}{\chi\eta_\Delta} \tag{18}$$

With $\eta_\Delta = 0.1$, $\chi = 0.8$,

$$b = 6$$

and the fractional energy error of (17) becomes 3% which is likely to represent a limit. The same limit can be reached with smaller η (hence smaller energy spread) and a correspondingly larger number of bunches b. The approximate general criterion for this, derived by making expression (17) equal to 3% for large b, small η_Δ and $\chi = 0.8$ is

$$\eta_\Delta b \sim 0.5 \tag{19}$$

This means, however, that a given linac, operated in compensated multi-bunch mode without any other modification, can yield an approximate five-fold increase of beam power and luminosity at the price of a 20%

reduction in energy compared with single-bunch operation. The missing energy can be restored by an increase of total active length and total average RF power $\langle P_{RF} \rangle$ by $\chi^{-1} = 1.25$. Thus it may be said that compensated multibunch operation holds the promise of RF to beam efficiencies at or above 25%.

Whenever the accelerating gradient E_0 can be increased at given bunch population the resulting decrease of η_Δ and concomitant energy spread $\eta_\Delta/2$ is now welcome, since efficiency can be maintained by increasing b and decreasing τ_b, so long as the final focus system permits this and $\tau_b f$ can be made an integer.

TABLE 2

Case C of Table 1 modified for compensated multibunch operation.
Parameters for one linac

Case	C'	C"	
Final energy eU	1	1	TeV
Frequency f	29	29	GHz
Accelerating field E_0	80	160	MV/m
Filling factor for first bunch χ	0.8	0.8	
Average accelerating gradient χE_0	64	128	MV/m
Total active length L_{tot}	15.6	7.8	km
Peak power per section length $\hat{P}_L/L$	96	386	MW/m
Bunch population N	5.35×10^9	5.35×10^9	
Energy extraction η	0.08	0.04	
Energy spread within bunch $\eta_\Delta/2$	5%	2.5%	
Number of bunches per pulse b	6	11	
Repetition rate f_{rev}	5.8	3.2	kHz
Average RF power $\langle P_{RF} \rangle$	100	100	MW
Beam power $\langle P_b \rangle$	30	30	MW
Structure fill time τ	11.4	11.4	ns
Bunch interval τ_b (not adjusted for integer $\tau_b f$) .	0.456	0.228	ns
RF cycles between bunches $\tau_b f$ approx.	13	7	
Beam pulse duration $(b-1)\tau_b$	2.28	2.28	ns
Luminosity	0.6×10^{34}	0.6×10^{34}	$cm^{-1}s^{-1}$

Table 2 gives two examples of 1 TeV compensated multibunch operation at 29 GHz. The first column represents case C of Table 1 lengthened by 25%, the second one is the same linac at twice E_0. In both cases a luminosity of 0.6×10^{34} $cm^{-2}s^{-1}$ is obtained with 100 MW average RF power per linac at 30% RF to beam efficiency.

Two classes of fundamental problem must, however, be solved before compensated multibunching can be attempted. Firstly, a final focus scheme must be found that can cope with multiple bunch crossings starting at a few centimetres' (3.5 cm in Case C") distance from the main collision point. Secondly, higher-order longitudinal wakefields must be either minimized or their time dependence tuned in such a way as to make the bunch-to-bunch variation of effective accelerating field tolerable. Whether this can be achieved by structure design alone is not certain. Modulations of input power, bunch population or bunch interval τ_b (modulo f^{-1}) might be additional elements of freedom. Contrary to the energy spread within the bunch the residual bunch-to-bunch energy variation is unlikely to be a monotonous function of time and, hence, difficult to correct.

In the following discussion of a two-beam scheme examples B and C of Table 1, in single bunch mode, will be used for numerical examples. However, if compensated multibunching became possible it could certainly be applied to this scheme.

4. A two-beam scheme

A very serious problem with linac parameters such as those shown in Table 1 is the generation of peak power. At least for the lower part of the frequency range considered, it is likely to become technically feasible[3)] to power each linac section by an individual d.c. to RF converter, each one containing its own high-voltage input, cathode, gun, RF structure and collector. Above 3 GHz no suitable design is available yet but promising development work is going on[4)]. However, in addition to yielding the required performance, such converters must also be producible at extremely low cost, as more than 10,000 units will be typically required for a 1+1 TeV collider.

Alternatively, a continuous drive beam, running all along the main linac and delivering energy to it at regular intervals may be considered. A specific scheme, in which RF energy is extracted from the drive beam by means of free electron lasers and restored by induction linacs has been proposed[5]. Another proposal combines free electron lasers with superconducting RF drive linacs[6].

What is analysed below is the combination of a tightly bunched high-energy drive beam directly furnishing energy to RF cavities and a superconducting RF drive linac.

Efficiency is of paramount importance for the drive chain. Therefore, and since the drive beam pulse cannot extract more than a fraction of the drive linac's stored energy at tolerable energy spread the stored energy must be conserved from pulse to pulse. It follows at once that the drive linac has to be superconducting. This, however, is quite acceptable provided the drive linac's gradient and operating frequency can be made sufficiently low. Thus, the following concept presents itself for analysis.

The mains input power is converted to RF power at UHF frequency by means of large CW klystrons and distributed via low-cost sheet metal waveguides at atmospheric pressure. Klystrons of well over 1 MW CW output at efficiencies approaching 70% are available to-day[7]. A further extension of power per klystron seems possible, so that the total number of converters would hardly exceed 100 for a 1+1 TeV collider. The klystrons deliver power to a series of superconducting cavities very similar to those developed for circular e^+e^- colliders at CERN[8] and elsewhere. Drive beam pulses of a duration equal to the main linac fill time τ have their energy periodically restored by passing through this superconducting drive linac. The drive beam is bunched at the UHF drive frequency f_1 but the bunches are made so short as to interact directly with travelling-wave transfer structures of main linac frequency f, each transfer structure being coupled to the input of a main linac section.

Figure 1 shows the arrangement. Since the main linac section length will be under 1 m and the UHF drive linac cannot be sliced in such short sections, transfer structures and drive cavities cannot be interlaced. Thus, the drive linac length must be added to the total length unless two drive beams, each equipped with half the drive linac sections, are made to run along either side of the main linac powering it alternately from the left and from the right.

5. The drive linac

Energy conservation along the drive beam demands that

$$\hat{P}_L \tau = \eta_2 n_1 b_1 N_1 e p E_1 m L \quad . \tag{20}$$

Controlling the drive beam's energy spread and the mismatch at the drive linac's RF input means that

$$\eta_1 = \frac{p n_1 b_1 N_1 e \omega_1 r_1'}{E_1} \tag{21}$$

(the fraction of energy extracted from the drive linac) cannot be too large. Here η_2 is the efficiency of energy transfer by the drive beam, $n_1 b_1 N_1 e$ is the total charge of the drive beam pulse (distributed over n_1 drive linac cycles and b_1 bunches per cycle), m is the fraction of active main linac length occupied by drive linac sections and ω_1, r_1' and E_1 are the angular frequency, R over Q per unit length and accelerating gradient respectively of the drive linac. The factor p (≤ 1) expresses the fact that the drive bunches may not ride on the crest of the drive-linac wave. Together with equations (3) and (5) the two equations mean that

$$\boxed{\left(\frac{E_1}{E_0}\right)^2 = \frac{1}{\eta_2 \eta_1 m g^2} \frac{\omega_1 r_1'}{\omega \; r'}} \tag{22}$$

Since, obviously, E_1 should be much smaller than E_0 although η_2, η_1, m, g^2 are all smaller than unity it follows at once that ω/ω_1 must be made very large, as large as is technically possible. At least the right-hand side of equation (22) is proportional to the square of the frequency ratio since $r_1' \propto \omega_1$ and $r' \propto \omega$ for given cell geometry. Introducing the superconducting cavities' quality factor Q_1 one finds

$$\boxed{\langle P_1 \rangle = \frac{E_0}{\omega r' g^2} \frac{\omega_1}{Q_1 \eta_1 \eta_2} \; U} \tag{23}$$

for the total drive linac dissipation, eU being the total main linac energy. Note that the dissipation is independent of the drive linac's length so long as the limit for deterioration of Q_1 with increasing field E_1 is not reached. Note also that the dissipation does not depend on r_1'. Dividing by the overall cryogenic efficiency η_{cr} one obtains the cryogenic input power P_{cr} per drive linac.

The practical lower limit and approximate economic optimum of f_1 is likely to lie in the lower UHF range, just as for circular collider RF structures. An obviously interesting choice at CERN is 350 MHz. Inserting typical parameters one finds at once that the main linac frequency has to be near the upper end of the range considered so far - i.e. case B or C of Table 1 - to make the scheme viable. Table 3 shows two sets of drive linac parameters for 20 and 29 GHz main linac frequency, η_{cr}^{-1} = 500 and 1 TeV total energy per main linac. The actual drive linac is the same in both cases; L_1 = 2.5 km is its total length and U_1 = 15 GV its total voltage gain.

TABLE 3

Drive linac parameters for two main linac frequencies
Parameters for one linac

Case	B	C	
Main linac energy eU	1	1	TeV
Main linac frequency f	20	29	GHz
Main linac accelerating gradient E_0	40	80	MV/m
Main linac R over Q parameter r'	28	41	kΩ/m
Main linac fill time τ	20	11.4	ns
Fraction of main linac active length occupied by drive linac m	0.1	0.2	
Drive linac active length L_1	2.5	2.5	km
Drive linac frequency f_1	350	350	MHz
Number of drive bunch trains n_1	7	4	
Transfer efficiency assumed η_2	0.9	0.9	
Drive linac energy extraction η_1	0.1	0.1	
Drive linac R_1 over Q_1 parameter r_1'	270	270	Ω/m
Drive linac accelerating field E_1	6.2	6.0	MV/m
Drive linac total voltage gain U_1	15.5	15.0	GV
Drive linac quality factor Q_1	5×10^9	5×10^9	
Cryogenic efficiency assumed η_{cr}	2×10^{-3}	2×10^{-3}	
Total cryogenic input power $\langle P_1 \rangle / \eta_{cr}$	35.6	33.5	MW

The optimum choice of m (with twin drive beams as mentioned at the end of Section 4) will be that which equalizes the costs of the drive linac and of the main linac including its tunnel. The shortest overall length would result if both linacs were given equal lengths. With the values for structure constants and E_1 of Table 3, Case C, this would result in 5.6 km active length at E_0 = 178 MV/m. It seems unlikely that this extreme solution will coincide with the economic optimum.

6. The drive beam

The total required charge per drive beam pulse is given by equations (20) and (5) as

$$n_1 b_1 N_1 e = \frac{E_0^2}{\omega r' g^2 \eta_2 m p E_1} = \frac{E_0}{\omega r' g^2} \frac{U}{\eta_2 p U_1} \qquad (24)$$

Even with the drive bunches coinciding with the crest of the drive wave ($p = 1$) the total charge amounts to over 6×10^{12}e for both cases of Table 3. It can, at least, be divided into

$$n_1 = \tau f_1 \qquad (25)$$

bunches but, as n_1 is small (7 and 4 in cases B and C respectively), the population of such bunches would still be very large whilst their lengths σ_{1z} must be of the order of 1 mm or less in order to interact with the transfer structure at frequency f. A further subdivision into trains of b_1 bunches per drive cycle will be discussed in Section 8 together with the necessity of $p < 1$.

Assuming that the drive linac sections are distributed along the main linac the mean energy of the linac (its injection and dump energy) can be chosen rather freely. A minimum condition is that energy spread and transverse emittance do not make the drive bunches drift apart. The first is prevented if

$$\langle \gamma_1^2 \rangle > \frac{L_{tot}}{2\sigma_{1z}} , \qquad (26)$$

the second if

$$\langle\gamma_1\rangle > \frac{\varepsilon_{1n} L_{tot}}{4\sigma_{1z}} \left(\beta_{max}^{-1} + \beta_{min}^{-1}\right) \tag{27}$$

obtained by integrating over the mean square of angular deviation for a beam with invariant emittance ε_{1n} in a FODO structure with β_{max} and β_{min} amplitude function. For $\varepsilon_{1n} = 10^{-3}$ m, L_{tot} = 25 km, β_{max} = 7.5 m, β_{min} = 2.5 m and σ_{1z} = 1 mm both conditions are satisfied above 1.8 GeV. If the corresponding maximum beam radius σ_r = 1.5 mm should be too large for the aperture of the transfer structure a higher injection energy combined with lower values of β must be chosen. In principle a large fraction of the injection energy can be regained by deceleration in the opposite injection linac (at the price of transporting the beam past the opposite drive and transfer sections). If, instead, the drive beam is dumped the overall RF drive power is increased by a factor $m_0c^2\langle\gamma_1\rangle/eU_1$ (~ 20% for 3 GeV dump energy).

7. The transfer structure

The transfer structures through which the drive beam is threaded and to which it delivers energy are assumed to be short sections of travelling wave structure - of length ℓ, group velocity v_2, quality factor Q_2 and R over Q per unit length r_2' - coupled to the inputs of the main linac section by short lengths of waveguide (Fig. 1). The group delay τ_2 is chosen so that

$$\tau_2 = \frac{\ell}{v_2} = \frac{\tau}{n_1} = \frac{1}{f_1} \tag{28}$$

The n_1 drive bunches (or bunch trains) of b_1N_1 charge each succeed each other at that interval. (The subdivision into a train of b_1 smaller bunches per drive cycle will only be considered in the next section.) Therefore the transfer structure empties itself during the bunch intervals, each bunch finds an (essentially) empty structure and induces a wave train of duration τ_2. The power flow is made equal to $\hat{P}_L$ by proper choice of r_2'. The condition for this is

$$(b_1N_1e)^2\omega f_1 \ell r_2' = (b_1N_1e)^2\omega v_2 r_2' = 4\hat{P}_L \tag{29}$$

which is equivalent to

$$(b_1N_1e\omega)^2 \; r_2' \frac{v_2}{v} = 4\frac{E_0^2}{g^2r'} \tag{30}$$

This follows from the fact that each bunch (or bunch train) leaves behind an induced field

$$E_i = \frac{b_1N_1e\omega r_2'}{2} \tag{31}$$

and experiences half that field itself.

If $r_2' = r'$ and $v_2 = v$, i.e. if the transfer structure had the same characteristics as the main linac, equation (29) or (30) would imply

$$(b_1N_1)_{min} = \frac{2}{\eta g} N \tag{32}$$

where Ne is the charge that extracts a fraction η of the main linac energy. In practice the limitation of the drive linac voltage imposes a larger value of b_1N_1 via equation (24) so that $v_2r_2' \ll vr'$ by a large margin - factors 30 and 100 respectively for the two cases of main linac frequency considered. This is fortunate here since it permits designing the transfer structure for very low r_2' and hence with a large aperture, relative to λ, for a fat drive beam. Improvements in superconducting RF technology may permit an increase in E_1 and hence a decrease in drive beam charge but it seems unlikely that the transfer structure will become a limitation.

The attenuation constant of the transfer structure is given by $\omega\tau_2/Q_2$ and, hence, equals

$$\alpha_2 = \alpha \frac{Q}{Q_2 n_1} \tag{33}$$

Thus, provided $Q_2 \sim Q$, losses in the transfer structure will be quite small. They are assumed to be globally included in the transfer efficiency η_2 (which is taken as 90%).

8. Drive beam energy spread and bunch charge

Using a *single drive* bunch per drive RF cycle has two serious disadvantages. Firstly the charge per bunch becomes very large. Secondly, as the head of the bunch sees zero field and the tail twice the average, the energy spread becomes very large.

Both problems can be alleviated by distributing a number b_1 of drive bunches (not necessarily all of the same charge) over the rising slope of the drive wave so as to match the build-up of decelerating voltage in the transfer structure to the sinusoidal rise of drive linac field (Fig. 2a). The former equals

$$\frac{e\omega r_2' \ell}{2} \left[\frac{N_k}{2} + \sum_{i=1}^{k-1} N_i \left(1 - (k-i) \frac{f_1}{f}\right) \right] \qquad (34)$$

for the k^{th} out of b_1 bunches spaced in time by f^{-1}. The charge of the i^{th} bunch is N_i and losses in the transfer structure are neglected. The second term under the sum accounts for the fact that a fraction f_1/f of the wave induced by each bunch leaves the structure during the bunch interval f^{-1}. By a suitable modulation of the bunch charges N_i (namely a gradual reduction towards the end of the bunch train) expression (34) can be matched to a quarter sine wave from bottom to top.

The match is, however, not exceedingly critical. If ε is the maximum fractional mismatch the drive linac energy has to be increased by that fraction and the overall efficiency (including cryopower) decreases by the same fraction. If, for simplicity, bunches of equal charge N_1 are spread over one eighth of the drive cycle $b_1 = f/8f_1$ and $\varepsilon \sim 4\%$ since more than half of the deviation of sin 45° from linearity is compensated by the $\sum i$ term of expression (34).

Since the drive bunches now ride on the slope of the drive wave the charge eb_1N_1 in equations (20), (21) and (24) (taken with p = 1) must be replaced by

$$\sum_{i=1}^{b_1} N_i \sin\left[(2i-1)\frac{\pi\omega_1}{\omega}\right] \tag{35}$$

For uniform bunch population N_1 and $b_1 = f/8f_1$ as proposed above this amounts to approximately

$$N_1 b_1 \frac{\int_0^{45^\circ} \sin\phi \, d\phi}{\pi/4} = 0.373 \; N_1 b_1 \tag{36}$$

Thus p = 0.373 and equation (24) gives the total drive charge as

$$n_1 b_1 N_1 e = 2.68 \frac{E_0^2}{\omega r' g^2 \eta_2 m E_1} = 2.68 \frac{E_0}{\omega r' g^2} \frac{U}{\eta_2 U_1} \tag{37}$$

Making use of $b_1 = f/8f_1$ and $n_1 = \tau f_1$ one finds

$$\boxed{eN_1 = 21.5 \frac{E_0}{\tau f \omega r' g^2} \frac{U}{\eta_2 U_1}} \tag{38}$$

for the bunch charge. A small reduction of the numerical factor can be expected from a modulation of bunch charges as mentioned above. Note that $N_1 \propto E_0 \, \omega^{-\frac{3}{2}}$ and that the only parameter of the drive linac entering is its total voltage gain U_1.

The drive bunch populations resulting from equation (38), namely,

3.5×10^{11} in case B
4.1×10^{11} in case C

(for $\eta_2 = 0.9$), are very high but do not seem obviously prohibitive for a beam whose transverse emittance can be rather large.

It should be noted that the peak field and dissipation of the drive linac - given by equations (22) and (23) - remain unaffected by the compensation of energy spread.

In reality the heads of all but the first drive bunch trains find a residual voltage in the transfer structure. Even if the travelling waves had perfectly sharp ends the residual voltage would amount to 1/16 with the scheme adopted above and dispersion will make it worse. This can be compensated by suppressing the first one or two of the b_1 bunches in all but the first of the n_1 bunch trains. An additional adjustment can be obtained by shortening τ_2 a little below f_1 , at the price of a small modulation of power flow to the main linac.

What remains to be taken into account is the 10% drop of drive linac stored energy (with $\eta_1 = 0.1$) and the phase shift of the drive wave caused by the off-peak passage of the drive bunches. The former can be matched by a 5% decrease of charge from the first to the last drive bunch train (accepting a 5% droop of main linac field during τ). The latter amounts to $1.34\eta_1\cos(\pi/8)$ radian or 7.1° per drive pulse. The klystron drive should be stepped by that amount at every pulse to avoid reflection.

9. Intermediate energy storage

Some form of pulse compression might be envisaged in order to increase the peak power and hence the accelerating gradient. However, the only hope of achieving the necessary intermediate energy storage at tolerable losses rests with storage devices in TE-mode configuration or with making them superconducting. For instance the following scheme of twofold compression might be considered.

In addition to the drive linac cavities and transfer structures the drive beam is threaded through passive, self-contained storage structures tuned to 2f. The drive pulse is preceded by a storage pulse of duration τ. The storage bunches are arranged on the rising slope of the drive cycle just as the drive bunches but have half the charge and 1/2f spacing so as to charge the storage structure but not the transfer structure and main linac. The subsequent drive bunches (with spacing 1/f) are shifted by c/4f with respect to the storage pulses. They receive additional energy from the storage structure which they have to empty for good efficiency.

In order to avoid the build-up of a large energy spread the storage device too consists of a short transfer structure emptying itself into the main storage structure in a time f_1^{-1}. The storage structure reflects the wave deposited therein so as to make it reappear in the transfer structure when the drive bunches pass. A biperiodic π-mode transfer structure is required for two-way operation at high group velocity. Compared with other schemes for pulse compression this one has the advantage of not interfering with the main linac "plumbing". The gain is the equivalent of a twofold increase in E_1. It may well turn out, however, that the losses of even an over-moded TE configuration at room temperature are excessive and that the aperture of a structure at 2f cannot be made large enough.

10. Energy recuperation

In a main linac structure designed for small loss during the fill time a large fraction of the input energy reappears at the output. In order to recuperate this energy the output of each linac section may be connected to an input created at the subsequent transfer section as shown in dotted lines in Fig. 1. A recuperation pulse follows the drive pulse and transfers the energy back into the drive linac.

Like the drive pulse the recuperation pulse consists of $n_1 = \tau f_1$ bunch trains but the bunches are situated on the decreasing decelerating slope of the drive cycle and the phasing with respect to the transfer structures is for acceleration (Fig. 2b).

In order to match the reduced field appearing in the transfer structure to the essentially unchanged drive linac field the charge of the recuperation bunches is left unchanged but their number b_1^* per drive cycle is reduced in proportion to the field attenuation (e.g. from $b_1 = 10$ to $b_1^* = 7$ in case C for 50% leftover power).

The forward direction of the drive beam determines the direction of phase and group velocities in the transfer structure. This should limit any leakage of drive energy back into the preceding linac section to a small fraction. In addition directional couplers may be used.

For single bunch operation with $\alpha = 0.5$, $\eta < 0.1$ this recuperation scheme permits, in principle, a factor two increase in repetition rate, beam power and luminosity per given average klystron power, at very little extra expense and complication.

11. Summary and conclusions

At the price of increased peak power, the RF to beam efficiency of a normal conducting linac can be raised above 5% by making the fill time very short. Compensated multibunch operation holds the promise of up to 30% efficiency but higher-order wakefield problems have to be solved and a suitable final focus must be found.

The worst remaining problem seems to be the economic and efficient generation of peak RF power. The scheme proposed here consists of a limited number of CW UHF klystrons, a superconducting UHF drive linac (occupying only a fraction of the total length) and a tightly bunched drive beam of several GeV average energy, transferring energy from the superconducting linac to the main linac via short sections of transfer structures. This scheme appears to have the following advantages:

- Power is converted from d.c. to RF by a limited number of CW klystrons of proven design and high efficiency.

- The subsequent transport of energy and its conversion to nanosecond pulses at microwave frequency can be carried out at an efficiency that might approach 90% except for the cryogenic power of the superconducting linac which - at the present state of the art - amounts to about 35 MW for a 1 TeV main linac.

- The repetition rate - the only parameter left free to adjust beam power in a given design - is determined by the drive beam and main beam injectors alone.

- Proper phasing of several tens of thousands of main linac sections is automatically assured by the highly relativistic drive beam. Precise adjustments of timing and populations of the drive bunches are required for optimum efficiency but these adjustments are all carried out at the drive beam gun.

- Most of the electromagnetic stored energy unavoidably left in the main linac after the passage of the beam can be recuperated and stored in the superconducting drive linac.

The main problem with this scheme is the generation and acceleration to a few GeV of the very dense and intense drive bunches required (a few times 10^{11} elecrons in about 1 mm bunch length).

Present-day performance of superconducting UHF cavities (about 6 MeV/m accelerating field and a few times 10^9 Q-factor at 350 MHz) is already sufficient to make the scheme viable but limits the main linac gradient to about 100 MV/m and makes cryo-power an appreciable contribution to overall dissipation. Any progress in the development of superconducting cavities will, therefore, permit a further improvement of main linac performance.

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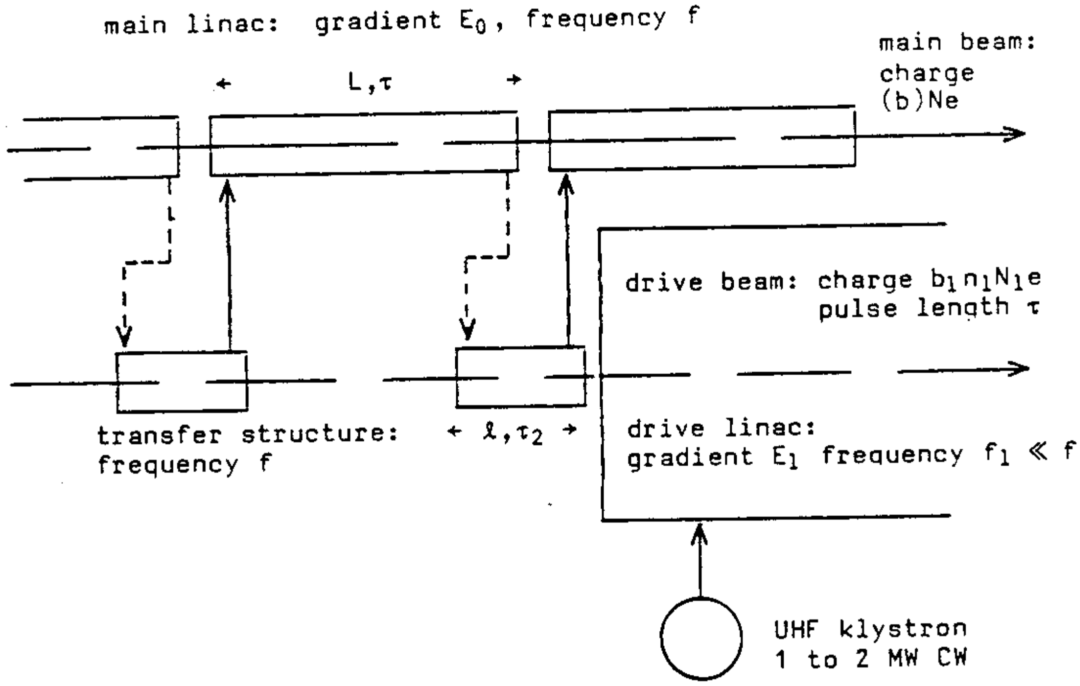

Fig. 1. Two-stage linear accelerator composed of a superconducting CW drive linac at UHF frequency and a microwave main linac. Typical parameters might be:

Main linac: 1 cm wavelength, 80 MV/m, 1 TeV final energy

Drive linac: 1 m wavelength, 6 MV/m, 15 GV voltage gain

Drive beam: 3 GeV, 4×10^{11} per bunch, 1 mm bunch length

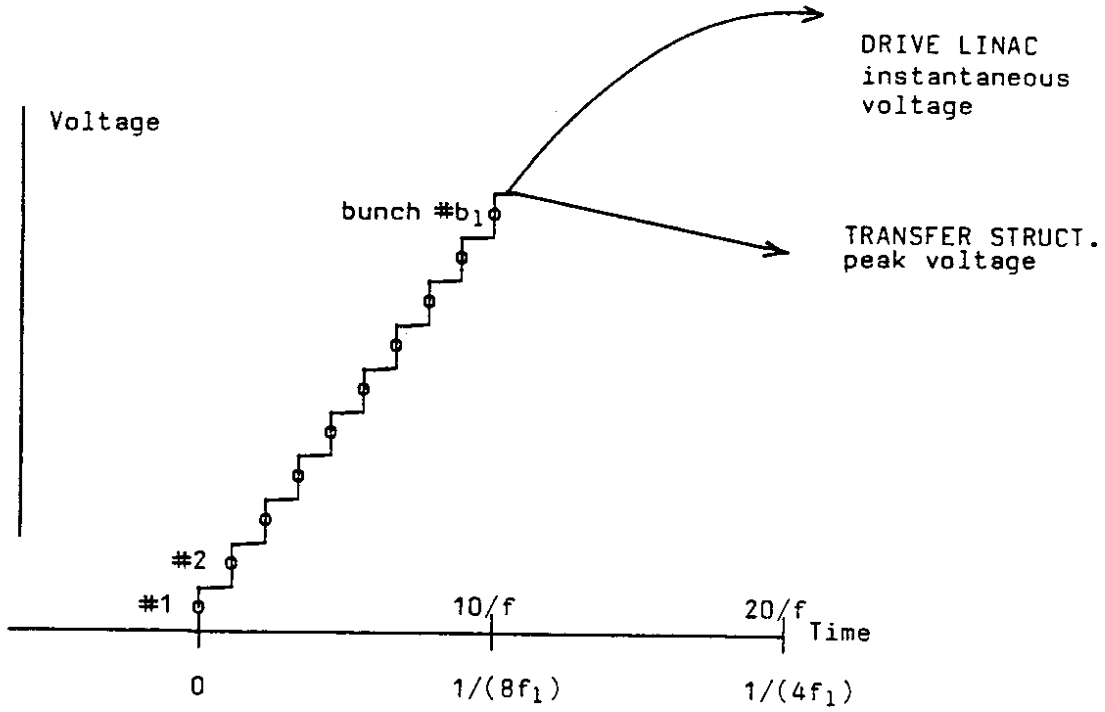

Fig. 2a. Matching of transfer voltage to drive voltage, Case C.

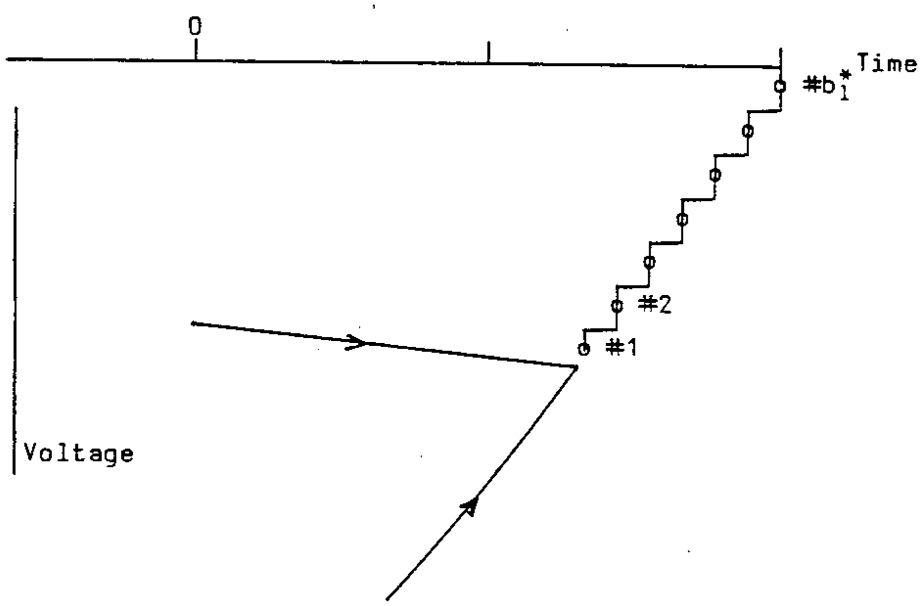

Fig. 2b. Energy recovery via the transfer structure.