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RADIO-FREQUENCY ACCELERATION FOR LINEAR COLLIDERS

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1. INTRODUCTION

This paper is concerned with the potentials and limitations of the classical RF linear accelerator, whose central part is a resonant structure made of copper or niobium, given a high quality factor (so as to maintain stored energy over a reasonable number of RF cycles) and driven from an external RF source. Such a structure is unlikely to yield accelerating gradients in the gigavolt per metre range. It should be noted, however, that 100 MV/m is already sufficient to permit building a 1+1 TeV collider within a total length not larger than the circumference of the LEP ring (27 km) - a full order of magnitude advance in energy per length.

This paper will deal with the problems of efficient acceleration. A choice of final focus based on classical beam radiation will be used for illustration but not discussed otherwise. An energy of 1 TeV per linac and a luminosity of at least $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ will be the aim of all numerical examples. Note that the situation changes rapidly with energy; as the required luminosity scales with energy squared the beam power decreases very rapidly with decreasing energy, permitting considerable relaxation of efficiency, average RF power and repetition rate at lower energies.

Most of this paper will be concerned with normal-conducting (copper) accelerating structures. The main problem here (from which nearly all other problems stem) is the limited Q-factor and the correspondingly short decay time of stored electromagnetic energy. If it were not for the inherent problems of RF superconductivity - limited gradient and cryogenic losses - nearly all problems could be eliminated and an ideal situation created by making the linac superconducting. Since this has, indeed, been proposed^{1, 2} the next section will deal with superconducting main accelerating structures.

2. SUPERCONDUCTING MAIN LINACS

A superconducting linac offers, in principle, the following, very impressive, advantages:

- Since the linac can be operated essentially in CW fashion, the repetition rate of beam pulses is determined by the gun and pre-injector only and can be very high.
- The stored energy, which will be large, because of the choice of a relatively low frequency, has a decay time very much longer than the repetition period. Therefore, the fact that each beam pulse extracts only a small fraction of stored energy does not impair efficiency while leading to the desirable feature of a small energy spread. The high RF to beam efficiency permits very high values of beam power and luminosity.
- Energy conversion from d.c. to RF can be provided by a relatively small number of CW klystrons of proven design, very high average power and high efficiency.

- The very large beam aperture, concomitant with a low frequency and with the special shape used for superconducting cavities, makes transverse wake fields harmless. Dampers, preventing higher resonant modes from ringing for times comparable with the repetition period, are, however, required.

A superconducting linac would be made of π -mode strings of resonators having the characteristically round shape shown in Fig. 1. These cavities are made from high heat conductance niobium sheet or, possibly, from copper sheet covered with a thin layer of niobium. Cryostats for 2°K are likely to be needed for the very high Q-factors (in the 10^{10} range) required here to keep the cryogenic input power below a reasonable limit.

Unfortunately the best accelerating gradients achieved so far in multicell structures of reasonable length hardly exceed 10 MV/m. Considerable further development is, therefore, required before a TeV linear collider with superconducting main accelerating structures may be envisaged. Laboratory results with single-cell resonators suggest that 25 MV/m (say) may be a reasonable goal for such a development. If this were achieved a 1+1 TeV collider would still require 80 km total active length. It would, however, permit very high luminosity to be reached - 10^{34} cm⁻²s⁻¹ for instance - with relatively modest amounts of RF power because of the near unity RF to beam efficiency of a superconducting structure.

The second unsolved problem with high-gradient superconducting structures is the cryogenic input power. Present-day Q-factors (in the upper 10^9 range at best) would make this power prohibitive under all circumstances. Even with $Q = 5 \times 10^{10}$ (say) the total cryogenic input would remain well above 1 GW for a 1+1 TeV collider in CW operation. It could be brought below 300 MW, however, by slowly pulsing the linac with 15% duty cycle (say) and a repetition period of several seconds, so that the on-time is long compared with the fill-time of the cavities but shorter than the time constant of the cryostats^{1, 2}.

In section 9 two-stage RF schemes using an auxiliary beam and a superconducting drive linac will be described. These schemes hold the promise of combining some of the advantages of RF superconductivity mentioned above - especially those concerning RF power sources and repetition rate - with the high gradient achievable in a copper main accelerating structure. It is very fortunate in this connection that the development of RF superconductivity is being actively pursued for other applications (circular colliders³, low energy linacs⁴) and further progress can be expected over the next few years.

3. NORMAL CONDUCTING LINACS, DEFINITIONS

It is now well established that copper structures, operated at the high microwave frequencies which are mandatory anyhow for minimizing stored energy, can support accelerating gradients of many hundred MV/m. Therefore, practicable accelerating gradients are entirely determined by available peak power rather than breakdown. Most of the discussion presented in this and the subsequent sections will, therefore, be concerned with peak and average power. The following simple model will be used for this discussion.

The linac is made of travelling wave sections of section length L , obtained by coupling resonators to each other so as to obtain the phase velocity c at the desired operating frequency $f = \omega/2\pi$. Each section is energized by a square power pulse of duration τ and peak power $\hat{P}_L$. This makes a wave front propagate in the section with group velocity v . The parameters are chosen so as to make τ the group delay or "fill time" of the structure which means that

$$\tau v = L \quad . \quad (1)$$

The power is shut off when the wave front has reached the end of the section. At this moment the bunch to be accelerated (or the last one of a train of bunches) is made to pass. For simplicity $v/c \ll 1$ will be assumed (although it may easily reach 10% in practice) so that the beam traverses a section in a time which is short compared with τ and the dilution of the wave front due to dispersion will be neglected. Constant group velocity (i.e. a "constant impedance structure") is assumed unless stated otherwise. Basic structure constants are the quality factor Q (the e-folding decay time of stored energy measured in RF radians) and the "R over Q per unit length" defined as

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

where $E(z)$ is the accelerating field and $W'(z)$ the stored energy per unit length at location z within a section. (Instead of r' the "fundamental frequency loss factor" $k_0 = \omega r'/4$ is often used.) The shunt impedance per unit length R' is defined by

$$R' = \frac{E^2(z)}{P'_D(z)} \quad (3)$$

where $P'_D(z)$ is the power dissipation per unit length.

Finally a dimensionless attenuation constant α for **stored energy** may be conveniently defined by

$$\alpha = \frac{\omega L}{Qv} = \frac{\omega}{Q} \tau \quad . \quad (4)$$

If a given structure geometry is scaled to different wavelengths,

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

The travelling wave linac assumed throughout this paper has the great advantage of offering a matched load at a single feed point per section. At very short wavelengths (well below 1 cm say) individually fed resonators might be necessary. Such arrangements which rely on a distributed power source and coupling device and entail power reflection during the fill time are outside the scope of this discussion.

4. NORMAL CONDUCTING LINACS, BASIC PARAMETERS

Clearly the peak input power $\hat{P}_L$ per section must exceed $E_0^2 L / R'$ for an average accelerating gradient E_0 . As this power is very high, a normal conducting electron linac is always pulsed with a very small duty cycle. On the other hand, as the Q-factor is much too small to conserve any appreciable fraction of stored energy over a realistic repetition period one is led to assume that the average RF input is roughly given by

$$\frac{\langle P_b \rangle}{\eta} \quad (5)$$

where $\langle P_b \rangle$ is the average beam power and η the fraction of stored energy extracted by the beam pulse. The beam power is given by

$$\langle P_b \rangle = b N f_r e U \quad (6)$$

and determines luminosity, b being the number of bunches per pulse, N the bunch population, f_r the repetition frequency and eU the final energy. The fraction of energy extracted

$$\eta = \frac{b N e \omega r'}{E_0} \quad (7)$$

[from equation (2)] cannot be large, certainly not above 10%, if the beam's energy spread - about $\eta/2$ - should remain acceptable or at least correctible. Note that $\eta \propto \omega^2 / E_0$ (because of $r' \propto \omega$) and that equation (7) contains only basic design parameters which have to be chosen just right in order to achieve the desired compromise between efficiency and energy spread. The requirement of making η approach 10% for good efficiency leads to the choice of very high frequencies, much above the customary 3 GHz.

In reality dissipation **during** the fill time is by no means negligible. If this is included the correct expression for the peak input power $\hat{P}_L$ per section of length L is found as

$$\frac{\hat{P}_L}{L} = \frac{E_0^2}{g^2 \alpha R'} \quad (8)$$

where

$$g = \frac{1 - e^{-\alpha/2}}{\alpha/2} \quad (9)$$

On the other hand, by combining equations (6) to (9) the average RF power is found to be given by

$$\langle P_{RF} \rangle = \frac{\langle P_b \rangle}{g^2 \eta} \quad (10)$$

instead of expression (5). Thus, the RF to beam efficiency is ηg^2 . Clearly a compromise has to be made between economy in peak power and average efficiency by a suitable choice of α (and hence $\tau = \alpha Q/\omega$). 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 in the context of a large collider. 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' , which is twice the minimum. The RF to beam efficiency is, thus, 0.78η .

For the small values of attenuation constant proposed here the use of a constant gradient (graded group velocity) changes very little. In equation (8) the factor $g^2\alpha$ in the denominator is replaced by α_0 , the attenuation constant at the input. In equation (10) the factor g^2 in the denominator is replaced by $\alpha_0/\ln(1-\alpha_0)^{-1}$. But making $P_b/\langle P_{RF} \rangle = 0.78\eta$ as before (by choosing $\alpha_0 = 0.4$) makes $\hat{P}_L R'/E_0^2 L = 2.50$, only 2.4% below the value of 2.56 found above for a constant impedance structure.

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 $10^{33} \text{ cm}^{-2}\text{s}^{-1}$ luminosity with $\sigma_r^* \sim 80 \text{ nm}$ beam radius and $H \sim 5$ 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.

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.

Two limitations are illustrated by this table. On the one hand it will be noted that at 6 GHz the common effort of ten successive bunches of the above population is required to achieve 8% extraction in spite of the very modest assumed gradient of 40 MV/m. It is not clear whether transverse wake fields and the final focus permit multiple bunches. And if such multibunching were to become possible it would be very desirable to increase the energy extraction per pulse considerably beyond 8% by means of the bunch-to-bunch compensation of energy errors described in section 5. As is shown in Table 1 the frequency has to be increased to almost 30 GHz in order to reconcile 8% extraction, a more acceptable gradient of 80 MV/m and the typical bunch population shown with single bunch operation.

On the other hand the bunch length $\sigma_z = 1$ mm required to limit the beam radiation parameter δ in the classical regime is actually incompatible with 1 cm wavelength as it would lead to excessive energy spread. Reducing σ_z and N by a factor two would essentially solve this problem but would reduce η to 4% unless at least two bunches per pulse can be used. One is led to conclude that the requirements of acceptable RF to beam efficiency and an accelerating gradient at least in the neighbourhood of 100 MV/m lead to the necessity of short wavelength - about 1 cm - and that the possibility of using several bunches per pulse is very desirable. The problem with bunch length would disappear, however, if the quantum regime of beam radiation could be reached at 1 TeV.

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	M Ω /m
Quality factor Q	9500	5030	4150	
$R'/Q = r'$	8.4	28	41	k Ω /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	5.35×10^9	
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}	$\text{cm}^{-2}\text{s}^{-1}$

5. HIGH EFFICIENCY OPERATION

The 6.3% RF to beam efficiency postulated in Table 1 is already above present-day routine. It is dependent on the achievement of high energy-extraction and short fill time. A further increase of efficiency might be obtained by one of the two following methods.

Firstly, the choice of $\alpha = 0.5$ implies that in the absence of beam loading 60% of the input RF energy reappears at the output of the acceleration section. With $\eta \sim 10\%$ about 50% will be left so that a factor two in efficiency could be gained if it were possible to recover this leftover energy and store it in a suitable way. The two-stage RF scheme described in section 9 holds the promise of doing just this without much extra expense. A more remote possibility might be a rectifying load. Conversion from microwave power to d.c. was in fact achieved⁵ a decade ago, albeit with a continuous wave at the level of tens of kilowatts, with about 80% efficiency.

Secondly, a more substantial increase of efficiency may be obtained by employing a train of bunches distributed over a certain fraction of the fill time τ . The charge of each bunch is limited by the maximum value of η and concomitant energy spread, but the bunch interval is adjusted so that the fresh influx of RF energy restores the average accelerating field from bunch to bunch⁶. In order to operate a given linac in this way one may pass the first bunch at time $\chi\tau$ when the propagating wavefront has filled the fraction χ of the accelerating structure. Clearly, this reduces the final energy by the same fraction (or necessitates lengthening of the entire installation by χ^{-1}) and $\chi = 0.8$ (say) may be an acceptable choice. It turns out that $\tau_b = \eta\tau/2$ is the right bunch interval for first order compensation of bunch to bunch energy difference. The last bunch is passed at time τ when the wave front has reached the end and this makes the number of bunches b equal to $1 + 2(1-\chi)/\eta$. For $\chi = 0.8$ and $\eta = 0.08$, $b = 6$.

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	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}	$\text{cm}^{-1} \text{s}^{-1}$

Table 2 shows two examples of compensated multibunch operation. Case C'' illustrates the flexibility of this scheme in accommodating higher accelerating gradients without increase of operating frequency or decrease of RF to beam efficiency which is as high as 30% in the cases listed.

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 wake fields must be minimized and their time dependence tuned in such a way as to make the bunch-to-bunch variation of effective accelerating field tolerable. Modulations of input power, bunch population or bunch interval τ_b might be elements of freedom. Contrary to the energy spread within the bunch the residual bunch-to-bunch energy variation is unlikely to be a monotonic function of time and, hence, difficult to correct.

6. ACCELERATING STRUCTURES

Of the three structure constants defined above R' determines peak power, r' the energy extraction and Q the fill time. Achieving the largest possible values is, therefore, important in all three cases. The values listed in Tables 1 and 2 are obtained from scaling SLAC-type disc-loaded structures and are likely to represent the very best available in practice. Unfortunately the low group velocity of such structures - of the order of $v/c = 0.01$ - would lead to the unacceptably short section length of about 3 cm at 1 cm wavelength. It would appear that $v/c = 0.1$ (say) leading to 34 cm section length is a minimum requirement. Since the group velocity grows with about the 4th power of the coupling aperture⁷ this can probably be obtained at the price of only a moderate deterioration of R' and r' . Thus, the disc-loaded guide might remain the solution once again. Test structures for 1 cm wavelength have, indeed been manufactured and tested⁸. This impressive work indicates that 1 cm may be close to a lower limit of wavelength for extrapolation of the classical travelling-wave linac.

Structures with even higher group velocity can certainly be built. The Jungle Gym is the most extreme example though one that does not seem to lend itself well to the very small transverse dimensions (5 mm diameter) required here. Several variants of related (bar loaded) structures are being studied at CERN with a view to linear collider application but preliminary results indicate that good shunt impedance cannot be obtained for the large beam apertures which are required because of the transverse wake fields discussed in section 10.

At the average power levels discussed here rather intense water cooling will be required. It is likely that the entire accelerating structure will have to be surrounded by tightly fitting, permanent magnet quadrupoles in order to cope with transverse wake fields. The manufacturing tolerances of a 1 cm disc-loaded structure are in the micrometre range⁸ and similar tolerances are likely to be required for transverse alignment of structures and quadrupoles.

7. RF POWER CONVERTERS

With linac parameters such as those shown in Tables 1 and 2 a very serious problem is the generation of peak RF power. At least for the lower part of the frequency range considered in Table 1 it is likely to become technically feasible to power each linac section - or small group of sections - by an individual d.c. to RF power converter, each one containing its own pulsed high-voltage input, cathode, gun, RF structure and collector.

The main limitation is in the electron gun where d.c. power must be converted to kinetic energy of electrons whose initial velocity is very low. Clearly the peak output power cannot exceed the product of input voltage, cathode current density and cathode area. The voltage is limited by breakdown, 0.5 MV now being considered an ultimate limit in practice. The limit for current density is given by space charge. In steady state and for a narrow gap the current density is inescapably determined by "Child's Law" ⁹ as

$2.3 \times 10^{-6} \frac{V^{\frac{3}{2}}}{d^2}$ where V is the voltage and d the gap width. Different geometry and the shortness of the pulse modify this but a basic limitation remains. The cathode dimension is related to the wavelength λ which means that the output power of a given design tends to scale with λ^2 . Impressive quantitative progress is, however, being made using beam compression after the cathode, overmoded RF cavities to interact with the beam or, possibly, distributed RF structures.

The classical pulsed klystron has reached output powers above 100 MW at 3 GHz¹⁰ but the λ^2 scaling does not make this look promising for an order of magnitude higher frequency. Laser driven optical cathodes will permit generation of the RF beam structure as well as the pulse envelope by suitable modulation of the laser, leading, in principle, to a very compact design not requiring an external modulator. Such lasertrons are being developed at SLAC, KEK and LAL Orsay. The expectation that optical cathodes can be applied to distributed RF structures has led to the concept of the Micro Laser-tron¹¹. The most advanced solution at the present time is the Gyroklystron. The longitudinal bunching of the normal klystron is replaced by gyration of the electrons at the cyclotron frequency in a longitudinal field and consequential bunching in transverse phase space. The gyrating electrons interact with TE-mode cavities of large aperture. Figure 2 shows a design¹² which features a Magnetron Injection Gun and hollow beam and aims at 30 MW peak output at 10 GHz being obtained in the near future.

In the likely event that a given power source produces insufficient peak power but more than the necessary pulse length, pulse compression may be applied. The most promising scheme is Binary Pulse Compression¹³. Power sources are used in pairs and their outputs are combined in a hybrid junction possessing two inputs and two outputs. A phase reversal in the low power drive of one of the power sources halfway through the pulse switches the power from one output to the other so that power pulses of half the original duration appear successively at the two outputs. Delaying one of these pulses with respect to the other and recombining them in another hybrid junction creates the desired output of double power and half pulse length. The scheme can be repeated using suitably coded phase

reversals in both power source drive chains so that power multiplication by factors of 4, 8 and 16 - minus the unavoidable losses - can be obtained. The main problem lies with the necessity of very low-loss delay lines of considerable length. Smooth waveguides in TE-mode, possibly superconducting, are expected to offer a solution.

In spite of all these developments it does not appear easy to power a 1+1 TeV RF collider with individual d.c. to RF converters. Column C of Table 1 indicates a total peak power of 2.4 TW at 80 MV/m gradient, necessitating many thousands if not tens of thousands of power converters. And this number would increase in inverse proportion to the accelerator length if this were shortened by using a higher gradient. The auxiliary beam schemes described in the next two sections are inspired by these considerations.

8. TWO-BEAM ACCELERATORS

Instead of the multitude of pulsed d.c. generators, cathodes and electron guns a continuous drive beam running along the main linac (or at least a good fraction of it) may be employed. The drive beam supplies energy to the main linac at regular intervals via transfer structures. The drive beam energy is restored, at the same or different intervals, by accelerating structures forming a "drive linac". Free electron lasers (FEL) and direct RF decelerating sections have been proposed as transfer structures, induction units and superconducting RF accelerating cavities as drive linacs. These possibilities will be discussed in this and the following section.

The first auxiliary beam scheme has been proposed by Sessler^{14, 15} under the name of Two Beam Accelerator (TBA). This is also the scheme that has, so far, seen the most extensive experimental development. In the TBA the drive linac is formed by induction units, directly driven by spark gaps or, preferably, being saturable induction devices¹⁶. The transfer devices are tapered FEL wigglers delivering RF power at 1 cm wavelength to a continuous rectangular waveguide from which it is coupled to the main linac (consisting of disc loaded sections running at very high gradients) at regular intervals. Figure 3 shows the principle. The power will be coupled out of the waveguide by special scoop-like RF septum couplers designed to avoid mode conversion in the overmoded rectangular guide. Among the impressive results achieved so far are the attainment of well over one GW RF power at 35 GHz from a FEL section, the fabrication of a 35 GHz disc loaded accelerating section and corresponding feeder waveguides and the actual attainment of 180 MV/m accelerating gradient⁸.

A basic feature of the FEL transfer structure is the limitation of drive beam energy to values below 100 MeV due to the fact that the generated wavelength is proportional to γ^{-2} times the wiggler wavelength. As the drive beam is only moderately relativistic the phase slip with respect to the main beam and the possibility of phase modulation causes problems. A variant of the TBA, the "Relativistic Klystron"¹⁷ replaces the FEL units by decelerating cavities directly extracting energy by the action of longitudinal fields on a bunched drive beam. It would appear that maintaining the induction units as drive linac still limits the drive beam energy and the total drive linac voltage gain for economic reasons.

9. TWO-STAGE RF SCHEMES

The drive linac of an auxiliary beam system may be formed by RF cavities. Since efficiency is of paramount importance here and energy extraction is again limited by energy spread, the RF drive linac has to be superconducting. This, however, is quite acceptable provided the drive linac's gradient and operating frequency is made sufficiently low. Since the superconducting drive linac is being run in CW regime d.c. to RF power conversion can be accomplished with large (1 to 2 MW per unit) high-efficiency klystrons of proven design. The beam repetition rate is determined by pre-injector considerations only and can be very high (above 5 kHz), as is indeed required for high luminosity. The possibility of energy recovery from the main linac is an additional advantage.

Energy transfer to the main linac may be via FEL units¹⁸ or RF decelerating sections¹⁹. The former solution requires bunching of the drive beam at the (low) drive frequency only but limits the drive beam energy to below 100 MeV just as in the TBA case. The latter scheme requires the drive beam to be very tightly bunched at the main linac frequency. It opens, however, the possibility of GeV drive-beam energies, thus eliminating all phasing problems. Proper phasing of several tens of thousands of main linac sections is automatically assured by the highly relativistic drive beam, all adjustments of drive-power, phase and timing being carried out at the drive beam pre-injector.

In either case the basic scheme is that shown in Fig. 4. 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. The klystrons deliver power to a series of superconducting cavities very similar to those developed for circular e^+e^- colliders at CERN²⁰ 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.

Energy conservation along the drive beam demands that the "transformer ratio", i.e. the ratio of the accelerating gradient, E_0 , in the main linac to that, E_1 , in the drive linac, be given by

$$\left(\frac{E_0}{E_1}\right)^2 = \eta_1 \eta_2 m g^2 \frac{\omega r'}{\omega_1 r_1'} \propto \frac{\omega^2}{\omega_1^2} \quad (11)$$

where η_1 is the energy extraction in the drive linac, η_2 the transfer efficiency, m the fraction of main linac length occupied by drive sections (an economic choice), $\omega_1/2\pi = f_1$ the drive frequency and r_1' the drive linac R over Q per unit length. Introducing the superconducting cavities' quality factor Q_1 one finds

$$\langle P_1 \rangle = \left(\frac{E_0 U}{\omega r' g^2} \right) \left(\frac{\omega_1}{Q_1 \eta_1 \eta_2} \right) \quad (12)$$

for the drive linac dissipation determining the input to the cryogenic system. Note the absence of m or E_1 in equation (12) and

the importance of keeping f_1 low. An interesting choice may be 350 MHz, the frequency of the superconducting cavities for the second stage of LEP. In fact, these cavities could be used at their present state of development without any change. Table 3 gives a few drive linac parameters.

TABLE 3

Main linac energy	eU	1	1	TeV
Main linac frequency	f	29	29	GHz
Main linac accelerating gradient	E_0	80	445	MV/m
Main linac active length	L_{tot}	12.5	2.24	km
Drive linac voltage gain	U_1	15	33.6	GV
Drive linac frequency	f_1	350	350	MHz
Drive linac R over Q parameter	r'_1	270	270	Ω/m
Drive linac accelerating gradient	E_1	6	15	MV/m
Drive linac active length	mL	2.5	2.24	km
Drive linac quality factor	Q_1	5×10^9	5×10^9	
Cryogenic input power	$\langle P_1 \rangle / \eta_{cr}$	35	186	MW

The first column is for the main linac of case C of Table 1 or 2. The corresponding drive linac parameters, $E_1 = 6$ MV/m and $Q_1 = 5 \times 10^9$ at 350 MHz are present-day performances²⁰. The second column shows the impressive main linac performance which can, in principle, be expected from an increase of E_1 to 15 MV/m, a development that is, in fact, likely to occur within a few years' time. In both cases, the total length of the superconducting drive linac is about 2.5 km. Since $m = 1$ in the second case, two drive beams, each equipped with half the drive linac sections, must be made to run along either side of the main linac powering it alternately from the left and from the right.

If the energy transfer to the main linac is by direct deceleration in an RF transfer structure the drive beam energy can be raised to a few GeV (3 to 5 GeV, say) by a modest addition to the superconducting drive linac. This would assure rigid drive bunches and the absence of any phase slip. The transfer structures can take the form of short travelling wave sections, each one coupled to the input of a corresponding main section via a short run of waveguide. The group delay of a transfer section τ_2 should approximately equal f_1^{-1} for continuous power flow. The required R' over Q of the transfer structure is very low, less than 1% of the main linac r' for the parameters chosen. This is fortunate since it will permit the design of a structure with large enough aperture to cope with the longitudinal and transverse wakefields due to the intense drive beam.

The required drive charge, unfortunately, is rather large and it has to be bunched. To be synchronous with the drive wave there must be $n_1 = \tau f_1$ bunch trains ($n_1 = 4$ for the parameters chosen). To be synchronous with the main linac each of the n_1 trains must consist of b bunchlets at f^{-1} interval. And in order to match the build-up of voltage in the transfer structure the b_1 bunchlets must coincide with the rising slope of the sinusoidal drive wave as shown in Fig. 5.

For the parameters of the first column of Table 3 $b_1 = 10$ and each bunchlet has to contain a population $N_1 = 4 \times 10^{11}$ (within about 1 mm bunch length). Phase modulation of the bunch train²¹ permits matching of the energies received from the drive linac and delivered to the transfer structure over as much as half a drive period. This brings about a reduction of the population to 6×10^{10} but necessitates a larger number ($b_1 = 40$) of shorter bunchlets. In either case the generation and acceleration to relativistic energies of the very dense and multiple drive bunches appears to be the main difficulty with this scheme.

Connecting the output port of each main accelerating section to an input of the following transfer section permits recovery of the leftover stored energy after the beam passage and, hence, a gain by a factor of two in power economy as pointed out in section 5. To do this, a recovery pulse has to follow the drive pulse. It has to be phased for acceleration in the transfer structure, deceleration in the drive linac and a reversal of the matching process shown in Fig. 5.

10. WAKE FIELDS

Each bunch induces longitudinal and transverse-deflecting wake fields as it passes through the accelerating structure. The wakes left behind by downstream particles act on the upstream part of the same bunch. Longitudinal wakes lead to energy loss and energy spread. Dipole wakes may amplify the amplitude of accidental transverse oscillations (due to misalignment of accelerating structures or quadrupoles) so as to cause severe emittance blow-up or even beam loss.

For axially symmetric structures fairly accurate computations of longitudinal and dipole wakes are available. They are based on the superposition of many modes of cavity resonance completed by extrapolation to very short wavelength with the help of an optical resonator model (cf. ref. 6 for instance). Figure 6a shows point charge wake potentials computed²² for a disc-loaded structure scaled from SLAC so as to resonate at 29 GHz. The beam hole diameter is 2.3 mm. the longitudinal wake (in V/As of energy loss per cell and unit of charge) starts with a very high value and comes down steeply with increasing distance (given in ps) from the inducing charge. The dipole wake (in V/Asm of transverse energy per cell and unit dipole moment of excitation) rises from zero to a maximum a few ps later.

Folding these curves with a Gaussian charge distribution and integrating one obtains the longitudinal and transverse wake potentials, $W_{||}(s)$ and $W_{\perp}(s)$ at position s within the bunch. Integrating all the way through the bunch gives the so-called loss factors $k_{||}$ and $k_{\perp}$ (shown in Fig. 6b) as a function of bunch length σ_z . The shape of the curve suggests that the transverse effect may be much reduced by making the bunch very short. It may be doubted, however, that the energy loss and spread due to the correspondingly large longitudinal wake could be tolerated. More realistic values of σ_z (a few tenths of a millimetre) will, unfortunately, result in near maximum values of $k_{\perp}$ which must, therefore, be made tolerable.

In the absence of any spread in transverse oscillation frequency within the bunch the action of transverse wakes is downright fatal as any accidental oscillation at the entry of a long linac is amplified by an enormous factor (typically 10^7).

The situation can, however, be rescued by the introduction of an energy spread within the bunch (or by tolerating the energy spread due to longitudinal wakes) so as to create a spread of transverse oscillation frequencies via the energy dependence of focussing^{23, 24}. If the combination of energy spread and focussing strength is below a certain critical value the wake-induced blow-up of an initial oscillation is only reduced - helpful but not sufficient in practice. If, however, energy spread and focussing strength are strong enough to fulfill a criterion^{23, 24, 25} given by

$$eN\dot{W}_\perp\sigma_z = 2\xi dU/\kappa_\beta^2 \quad (13)$$

the wake fields provide damping at the centre of the bunch and any blow-up is avoided. In equation (13) $\dot{W}_\perp$ is the slope of the wake field within the bunch (it is approximately constant within $\pm\sigma_z$), κ_β is the wavelength of transverse oscillations over 2π and d is the fractional energy deviation (assumed linear over the bunch) at σ_z . The particle energy is eU and $-\xi$ is the chromaticity of the focussing system, near unity in all practical cases. Note that it is U/κ_β^2 that matters. This means that the criterion is simultaneously fulfilled all along the linac if κ_β is made to grow with $\sqrt{U}$ by maintaining constant quadrupole strength. For $\dot{W}_\perp = 4.8 \times 10^{21}$

$\text{VA}^{-1}\text{s}^{-1}\text{m}^{-3}$ (transverse energy gain per dipole moment, per running metre of linac, per distance s behind the bunch head) $N = 5.35 \times 10^9$, $\xi = 1.27$, $\sigma_z = 0.3$ mm and $d = 1.3\%$ one finds $U/\kappa_\beta^2 = 19 \text{ GVm}^{-2}$ corresponding to a focussing wavelength $2\pi\kappa = 3.2$ m at 5 GeV. This means very strong focussing but is probably just feasible by means of small-aperture permanent-magnet quadrupoles surrounding the accelerator structure. The assumed value of $\dot{W}_\perp$ corresponds to a scaled SLAC structure with 2.3 mm holes. In reality somewhat larger holes will be necessary for acceptable group velocity (cf. section 6) making the situation more favourable at the expense of some loss in shunt impedance.

Extensive computations²² carried out at CERN and computations²⁶ carried out for TBA parameters essentially confirm equation (13) but show that wake field induced damping already sets in at slightly weaker focussing, albeit after a transient peak of blow-up immediately following the initial excitation.

Figure 7 shows the distribution of amplitudes at 1 TeV within $\pm 4\sigma_z$ of a bunch that has started with unity displacement at 5 GeV. The oscillation wavelength is 5 m at 5 GeV, increasing with $\sqrt{U}$: all other parameters are those listed above. The head of the bunch shows adiabatic damping as expected. At the centre the oscillation has damped out.

The values of energy spread in the percent range required for stabilizing the wake fields are unlikely to be acceptable to the final focus. Compensation may be attempted in the final part of the linac by suitable dephasing between bunch and wave. The question arises whether this can be done without, again, creating blow-up of oscillation amplitudes by wake fields. A first set of computations²⁷ indicates that this can, in fact, be avoided.

CONCLUSIONS

While a very large number of detailed problems has yet to be analysed the picture is emerging that RF linacs suitable for a 1+1 TeV collider are approaching potential reality.

By designing for heavy beam loading (close to 10% energy extraction) and an unusually short structure fill time an RF to beam efficiency above 5% seems possible with a single bunch per beam pulse. Multibunch operation raises additional problems but might increase the RF to beam efficiency by a factor five, typically.

An RF wavelength of about one centimetre seems to offer a feasible compromise between the hard requirement of low stored energy and the possibilities of extrapolating known microwave technology. The disc-loaded accelerating structure is a definite candidate but all details concerning manufacturing methods, tolerances, cooling, pumping and focussing have yet to be studied.

The peak power problem may be solved by auxiliary beams receiving their energy from drive linacs. A two-stage RF scheme employing superconducting RF drive cavities and drive beams of several GeV energy looks attractive, provided the necessary drive beam can be generated in the first place.

The potentially fatal problem of transverse wake fields can be eliminated by very strong focussing (quadrupoles all along the linac) and keeping a few percent momentum spread. Even so alignment tolerances will be very tight for conserving the small required emittance.

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Fig. 1 (from ref. 20). Characteristic shape of a four-cell π -mode superconducting cavity. The dimensions given are for 352 MHz, suitable for storage rings (LEP) or for the drive linac of a two-stage RF scheme. A superconducting main linac might run at 1 to 1.5 GHz.

Fig. 2 (from ref. 12). Arrangement of four-cavity gyrokystron

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Fig. 3 (from ref. 8). Two-Beam Accelerator

Fig. 4 (from ref. 19). Two-stage linear accelerator composed of a superconducting CW drive linac at UHF frequency and a microwave main linac.

Fig. 5 (from ref. 19). Matching of transfer voltage in a two-stage RF scheme with RF transfer structure.

Fig. 6 (from ref. 22).

(a) Point charge wake potentials for a disc-loaded cell scaled from SLAC to 29 GHz. The beam aperture has 2.3 mm diameter.

Longitudinal wake $W_{||}$ in V/pAs per cell, transverse wake $W_{\perp}$ in V/nAsm per cell, abscissa in ps behind inducing charge.

(b) Total loss factors $k_{||}$ (longitudinal) and $k_{\perp}$ (transverse) as functions of bunch length.

Fig. 7 (from ref. 22).

Distribution of transverse oscillation amplitudes at 1 TeV (12.4 km of linac) within $\pm 4\sigma_z$ of a bunch that has started with unity transverse displacement at 5 GeV. In the head (to the right) the oscillations have undergone adiabatic damping. Around the centre additional damping has occurred due to the wake fields. The focussing wavelength λ_β is 5 m at 5 GeV increasing with the square root of energy. The energy spread is linear within the bunch and $\pm 2\%$ at $\pm\sigma_z$. The chromaticity is 1.27, the bunch population $N = 5.35 \times 10^9$, $\sigma_z = 0.3$ mm and the structure is scaled from SLAC to 29 GHz with 2.3 mm aperture. Computation with 60 superparticles.