A TWO-STAGE RF LINAC FOR CLIC

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ABSTRACT
At CERN a feasibility study is under way for a linear electron-positron collider (CLIC). The c.m. energy is assumed to be 2 TeV and the luminosity above $10^{33} \text{ cm}^{-2} \text{s}^{-1}$. Such a machine requires a very high accelerating gradient and efficiency in order to keep length and power consumption within reasonable limits. For that purpose it is proposed to use a high-frequency accelerating structure which is powered by a steady-state drive linac running in parallel to the main linac.
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1. INTRODUCTION

In the early nineties the HEP community in Europe will have the option to place a Large Hadron Collider (LHC) with a c.m. energy of about 16 TeV and a luminosity of $10^{33}$ cm$^{-2}$ s$^{-1}$ in the LEP tunnel. However, a project of that size and cost, although scientifically attractive and technically feasible, has probably to fit into a world-wide programme.

It thus seems highly desirable or even necessary to have alternative options available. There, the general feeling is that such an option might be a linear electron-positron collider with 1 to 2 TeV c.m. energy and a luminosity above $10^{33}$ cm$^{-2}$ s$^{-1}$. However, the energy is one order of magnitude higher than in the SLAC machine (SLC), and the luminosity nearly three orders of magnitude higher. This requires more than simple extrapolation.

At present, two different approaches seem possible: one is a conventional linac with an RF frequency 3 to 4 times higher than usual, which is driven by a large number of very high power klystrons (several hundred megawatts output power). The second is a so-called two-beam accelerator (TBA). The main linac, with an RF frequency 5 to 10 times the standard frequency (3 GHz), is powered by a periodic array of transfer lines coming from a drive linac which runs in parallel. The drive-linac beam is alternately decelerated, for RF generation purposes, and reaccelerated, thus keeping its energy constant.

In the following we will present a special TBA scheme, as is under discussion for CLIC.

2. TWO-BEAM ACCELERATORS (TBAs)

A TBA consists of a high-energy low-current main linac plus a low-energy high-current drive linac running in parallel (Fig. 1). The RF is generated in a periodical arrangement of decelerating units and transferred to the main linac via waveguides. The energy lost in the drive beam by RF radiation generation is replenished in reacceleration units.

In the original proposal for a TBA [1], the RF was generated by free-electron laser (FEL) units. For the reacceleration, conventional-induction accelerating cells were foreseen. The main accelerating structure was a disk-loaded guide (DLG) at 34 GHz. Joint experiments between Berkeley LBL and Livermore LLNL [2] reached up to 1.8 GW FEL radiation, and accelerating gradients as high as 190 MV/m. Problems encountered in this scheme are RF phase control, inhibition of side-band instabilities and the long-distance transport of a relatively low-energy beam necessary for the FEL.

In a later proposal [3] the induction units have been replaced by 350 MHz superconducting cavities as developed for LEP.

In another modification of the original TBA, the FEL is replaced by a beam-cavity interaction, as for normal klystrons [4]. The advantage is that the interaction is simple and well understood, as compared with an FEL. The RF phase control and the side-bands are not expected to be a problem.

Finally there is a kind of synthesis of different ideas about TBAs, the aim being to eliminate weak points. It is the CERN proposal for CLIC [5] called the two-stage RF linac. It employs a high-energy
drive beam (~ 5 GeV) in order to minimize problems of phase stability and beam transport. The RF generation units are 30 GHz travelling-wave structures. Reacceleration is done by 350 MHz superconducting cavities, thus ensuring a high efficiency. The main accelerating structure is still a 30 GHz DLG.

3. WHY TBAs?

To create a 100 MV/m accelerating gradient in a copper structure, one needs typically 260 MW/m peak RF power at 3 GHz. A 2 TeV collider therefore requires 20000 SLAC klystrons of 65 MW each, plus a pulse-compression system which doubles the power level. Such a system certainly will cause serious problems as regards reliability and costs. On the other hand, a TBA may allow us to reduce drastically the number of units and their complexity.

For a 2 TeV collider the operating frequency of the liracs plays a fundamental role. Peak and average RF power scale with frequency as

\[ \dot{P}_{RF} \propto f^{-1/2}, \quad \bar{P}_{RF} \propto f^{-2} \]  

and the electrical breakdown problems decrease with increasing frequency. So, one would like to go to the highest possible frequency, which today is considered to be somewhere around 30 GHz. But there is no very high power source available for such a high frequency. Klystrons are probably limited to around 10 GHz, since the RF power is proportional to the beam area and therefore proportional to \( f^{-2} \). Gyro-klystrons are expected to perform a little better at high frequency, since the use of ring beams and overmoded RF structures allow a larger beam area. But it is unlikely that we will find a tube with about 100 MW output power above 15 GHz in the near future. This means that, instead of ten thousand tubes we would need a hundred thousand.

Finally, a TBA promises the required power levels even at 30 GHz. It only needs plumbing for RF generation and transfer, which should not be a problem despite the high number of components. The repetition rate can be high, a few kHz, as compared to about 100 Hz for tubes, and is determined by the injector only. The beam is reused after RF generation and can be reaccelerated by superconducting cavities. A high efficiency should therefore be possible. Problems of RF phasing are only caused by the injector, since the RF is locked on a stiff beam.
4. TWO-STAGE RF LINAC [5]

4.1 DRIVE LINAC

The drive linac employs a high-intensity ($1.6 \times 10^{13}$ electrons per RF pulse), medium-energy (3-5 GeV) beam. It is rapidly pulsed with 5.8 kHZ, a limit determined by the injector only. The beam passes a periodic arrangement of decelerating structures, where it creates RF radiation, and reaccelerating cavities. The decelerating structure (Fig. 2) is a travelling-wave structure of length $l_D$ operating at 30 GHz. It is rapidly filled by the beam, in a time $t_0 = l_D/c_0$, and then radiates during a delay time of $t_D = l_D/v_{D1}$ ($v_{D1} = 0.3c_0$ is the group velocity). When filling the structure the beam loses energy which has to be replaced in reaccelerating cavities. These are superconducting 350 MHz standing-wave cavities (Fig. 3) as developed for LEP. They will be powered by highly efficient, around 70%, klystrons of more than 1 MW each. The reacceleration system will operate in c.w. mode, ensuring a high overall efficiency.

Since the total charge in one RF pulse is very high, it is split into four bunches separated by 85 cm, a distance equal to the wavelength of the 350 MHz system (Fig. 4a). The delay time of the decelerating structure has then to be 2.8 ns, so that four radiation pulses make up for the filling time $t_F = 11.2$ ns of the main accelerating structure. But even with four bunches, the charge per bunch is still high. So, each bunch has to be split again into ten bunchlets separated by 1 cm, i.e. the wavelength at 30 GHz. When such a bunchlet passes the decelerating structure, it 'feels' its own induced voltage plus the voltage induced by all bunchlets in front of it. Thus the decelerating voltage for the bunchlets follows a linear characteristic (Fig. 4b). In order to match this voltage loss with the reacceleration, the bunchlets have to be placed on the rising slope of the sinusoidal reaccelerating field.

There are several reasons for the high main-linac frequency and the relatively low frequency of the reacceleration system: in the main linac one wants the high frequency in order to keep the RF power consumption reasonable and to obtain a safe high-field operation. The superconducting reacceleration system prefers a low frequency when the efficiency is high. Finally, the ratio of main accelerating gradient to reaccelerating gradient is proportional to the ratio of the corresponding frequencies.

Fig. 2 A 30 GHz travelling-wave structure for beam-induced RF radiation generation.
Fig. 3  Schematic view of a four-cell superconducting cavity and its cryostat module.

Fig. 4  a) Bunch structure in the drive linac and b) the matching of the decelerating and reaccelerating voltage.
4.2 MAIN LINAC

The present-day standard frequency for linacs is 3 GHz. But it is a general belief that a future high-energy machine will employ a higher frequency for reasons of RF power savings [Eq. (1)]. The upper limit, probably, will be around 30 GHz, determined by manufacturing requirements, cooling and high-power handling capacity. This is the frequency chosen for CLIC. It allows a factor of 100 lower RF average power and a factor of 3 lower RF peak power as compared to 3 GHz. A high-gradient operation, around 300 MV/m, should be possible but would require a prohibitive RF peak power of 1 GW/m. Therefore the accelerating gradient was fixed to around 100 MV/m, which is believed to be a good compromise between linac length (10 km), peak-power level (100 MW/m), and safe operation.

There are many different slow-wave structures capable of accelerating electrons. A few are shown in Fig. 5. But weighing the possible advantage of a specific structure against the requirements for a high-gradient 30 GHz structure, it turned out that the standard DLG is the most suited. The iris opening, and therefore the cell-to-cell coupling, is determined by a compromise between the wish for a high group velocity, i.e. rapid filling, and low wake fields (see later) and the need to keep the RF power as low as possible for a given gradient. These considerations resulted in

- group velocity $v_g = 0.07c_0$
- filling time $t_f = 11.2$ ns
- structure length $\ell = 25$ cm (around 70 cells).

Fig. 5 Different slow-wave structures for electron linacs.
Apart from the mechanical difficulties, the most serious problems are caused by the co-travelling electromagnetic fields of the beam. They are scattered at the surrounding chamber and act back on the beam. Normally they are described by so-called wake potentials. These are the components of a vector potential \( \vec{W} \) which are experienced by a probing charge following an exciting charge \( Q \) with constant velocity \( \vec{v} \) and distance \( \nu r \)

\[
\vec{W}(r) = \left( \frac{1}{r} \right) \int_0^l \vec{E} + \vec{v} \times \vec{B} \, ds.
\]

The longitudinal component leads to energy loss and energy spread in a bunch. The transverse components deflect particles and may cause emittance blow-up or even beam loss.

Figure 6 shows the effect of transverse wake fields (example from Ref. [6]). What is shown is the shape of a bunch at the end of the linac, which was injected with a transverse offset of 1 unit. For this purpose the bunch was cut into longitudinal slices, and the dots indicate the transverse position of the slice centroids. As can be seen, the 'tail' of the bunch is blown up by a factor of 800.

To cure the disastrous transverse effects, different measures have to be taken:
- Widening the structure iris; since the transverse wake potential and the length \( L \) of the machine scale with the iris radius \( a \) as

\[
W_T \propto a^{-2.8} \quad L \propto a^{-0.8}
\]

one can decrease the transverse effects without increasing the length too much.
- Shortening the bunches; this would help decreasing the transverse effects if the r.m.s. bunch length is \( \leq 0.01\lambda_{RF} \). But we do not know how to make these short bunches, and even if we would the longitudinal effects become pretty bad.
- Very strong focusing; this is in any case needed for the very small beam emittances required in the linac. Additionally, it helps since the transverse wake is proportional to the transverse offset. On the other hand, a strong focusing system is very sensitive to quadrupole displacements. In the example of Ref. [6], the allowable quadrupole displacement jitter was found to be of the order of 0.1 \( \mu \text{m} \).
- Landau damping; the usefulness of an energy spread in the bunch to inhibit blow-up was pointed out elsewhere [7]. If the 'tail' of a bunch has a lower energy than the 'head' it will be more focused, i.e. it will advance in betatron phase. At the same time the 'tail' experiences the wake field of the 'head' in such a way that it is kicked away from the machine axis, which means that it will lag behind in betatron phase. So, one effect can compensate the other by choosing the right energy spread. Because of the non-linear shape of RF voltage and longitudinal wake field, the compensation is not perfect as can be seen in Fig. 7. The 'head' particles, not subject to wake fields, oscillate freely with an amplitude corresponding to adiabatic damping. Core and 'tail' of the bunch are damped even more by constructive complicity of the wakes.

A disadvantage of this scheme is the high energy spread in the bunch, between 1 and 2\%, needed for an effective damping.
- RF focusing [8]; an RF structure with slotted irises has the property that a charge passing off-centre in the direction of the slot 'sees' only a magnetic field and is therefore focused. Perpendicular to the slot it 'sees' the focusing magnetic force plus a defocusing electric force which is twice as large. Such a cavity forms an RF quadrupole. The focusing strength is proportional to the accelerating field and, for CLIC, of the order of 100 T/m.

The advantages of an RF focusing system are:
1) The focusing acts within the bunch scale, i.e. different parts of the bunch are focused differently, and the spread in betatron oscillation, necessary for Landau damping, is introduced without a large energy spread.
2) The spread is so large that the focusing strength can be reduced by more than one order of magnitude. The resulting alignment jitter tolerances for quadrupoles are then 10 to 20 \( \mu \text{m} \) as compared to 0.2 \( \mu \text{m} \) for external focusing only. Figure 8 (from Ref. [9]) shows the transverse bunch...
shape at the end of the linac in case of a focusing system which is half external and half RF focusing. The quadrupoles are misaligned randomly with an r.m.s. value of 1 μm.

3) The savings in precision permanent magnets.

4) The accelerating cavity, now forming the focusing system, may be used to observe a beam-induced, higher-mode signal for automatic control.

Fig. 6 Transverse bunch shape at the end of the linac. Bunch offset at injection is 1 unit. (From Ref. [6].)

Fig. 7 Transverse bunch shape at the end of the linac in the case with Landau damping, as compared to Fig. 6 (without damping).
4.3 DESIGN PARAMETERS

Table 1 gives some possible parameters for a 1 TeV two-stage linac which would allow a luminosity of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ in the collider mode. The first column is for an accelerating gradient of 6 MV/m in the superconducting reacceleration cavities, corresponding to the present-day performance. The second column reflects the enormous improvement which can be expected from an increase to 15 MV/m which is likely to occur during the coming years.

<table>
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<tr>
<th>Main linac</th>
<th>Drive linac</th>
</tr>
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<tbody>
<tr>
<td>frequency (GHz)</td>
<td>frequency (MHz)</td>
</tr>
<tr>
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<td>350</td>
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<tr>
<td>accelerating gradient (MV/m)</td>
<td>accelerating gradient (MV/m)</td>
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<td>6</td>
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<tr>
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<td>quality factor (10^9)</td>
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<tr>
<td>bunch population (10^9)</td>
<td>cryogenic input power (MW)</td>
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<td>repetition rate (kHz)</td>
<td>active length (km)</td>
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5. CONCLUDING REMARKS

World-wide there exist two serious approaches to a 1 + 1 TeV linear collider. One is based on a more conventional linac, around 10 GHz, powered by ultra-high-power klystrons. The other—more daring—is a two-beam device.

We have focused on the second approach, which we believe to be simpler in construction and where we expect a lower power consumption.

The main linac consists of a high-frequency structure, between 20 and 30 GHz, and a mixed scheme of external and RF AG-focusing, in order to manage the otherwise fatal wake-field problems. The structure performance and beam dynamics have to be further studied. Fabricational techniques as well as alignment and beam steering possibilities have to be developed.

For the drive linac, the RF generation units are being studied and the reacceleration system is hoped to consist of existing superconducting cavities as developed for LEP. The beam-loading problem and the resulting beam microstructure have still to be studied. Questions concerning phase precision, stability and control are not yet addressed.

Finally, there remain all the problems on the injector and intersection side. The main-linac injector has to provide a beam with an emittance one order of magnitude lower than at the SLC, at a high repetition rate, a few kHz, and with short bunches, typically 0.3 mm. The drive-linac injector operates at the same repetition rate and with a very high current density. Additionally, it has to ensure a very precise beam microstructure. At the intersection the beam–beam interaction is still not fully understood and a final focus has to be found which will be capable of producing a beam size of some 10 nm in the presence of a relatively high energy spread.

REFERENCES


