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COLLECTIVE ELECTRON DRIVEN LINAC FOR HIGH ENERGY PHYSICS*

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Summary

A linac design is presented in which an intense ultrarelativistic electron bunch is used to excite fields in a series of cavities and accelerate charged particles. The intense electron bunch is generated in a simple storage ring to have the required transverse and longitudinal dimensions. The bunch is then transferred to the linac. The linac structure can be inexpensively constructed of spacers and washers. The fields in the cells resulting from the bunch passage are calculated using the program BCI[1]. The results show that certain particles within the driving bunch and also trailing particles of any sign charge can be accelerated. With existing electron storage rings, accelerating gradients greater than 16 MV/m are possible. Examples of two accelerators are given: 1) A 30 GeV electron/positron accelerator useful as an injector for a high energy storage ring and 2) a 110 GeV per beam electron-positron collider.

A Collective Electron Driven (CED) Linac

The electromagnetic fields generated by the passage of a relativistic bunch of charged particles through a cavity accelerate every particle in the bunch. The fields and ensuing accelerations depend on the charge distribution of the bunch and the geometric and electromagnetic properties of the cavity. The accelerating voltage in the direction of the trajectory of the particle integrated over the passage of the bunch through the cavity (the longitudinal wake potential) varies with the particle's longitudinal position. The cumulative effects on the bunch which encounters many such cavities drastically change the energy distribution within the bunch and ultimately the charge distribution. The goal of an accelerator using this technique is to maximize the transfer of energy from the majority of the particles in the bunch to a relatively small fraction, hopefully useful for high energy physics. Similar accelerators using proton beams are considered in Ref. 2 and low energy electrons in Ref 3.

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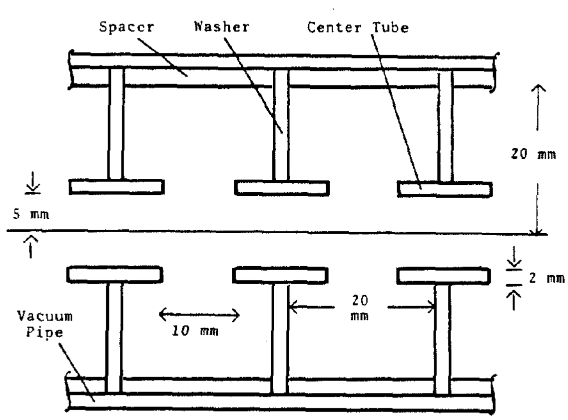

Fig. 1 Simple cavity design for a CED linac.

Cavity Design and Wake Potentials

The cavity design must provide for the passage of the bunch and for sufficient coupling to the bunch to provide acceptable acceleration. It need not sustain long term fields. The longitudinal wake potentials studied here were generated in the time domain using the program BCI[1] which performs a numerical integration of Maxwell's equations. Many cavity shapes were studied and several of vastly different designs had wake potentials satisfactory

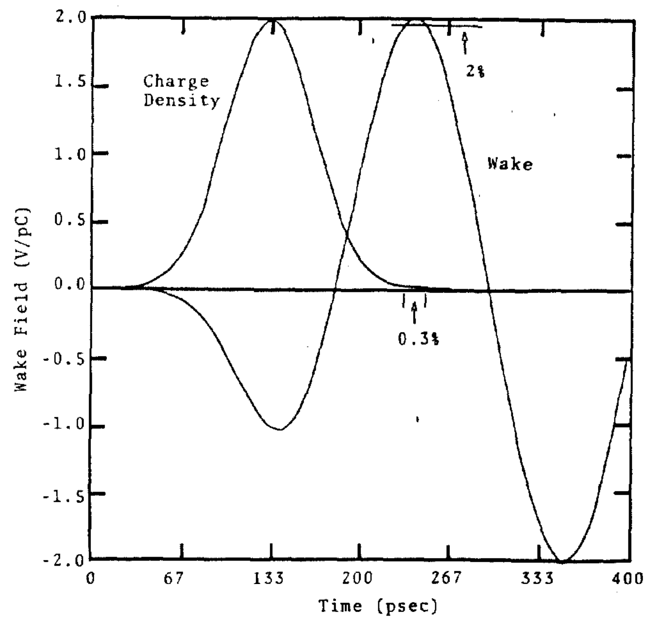

Fig. 2 Longitudinal wake potential for one cell. Gaussian bunch length is 1 cm.

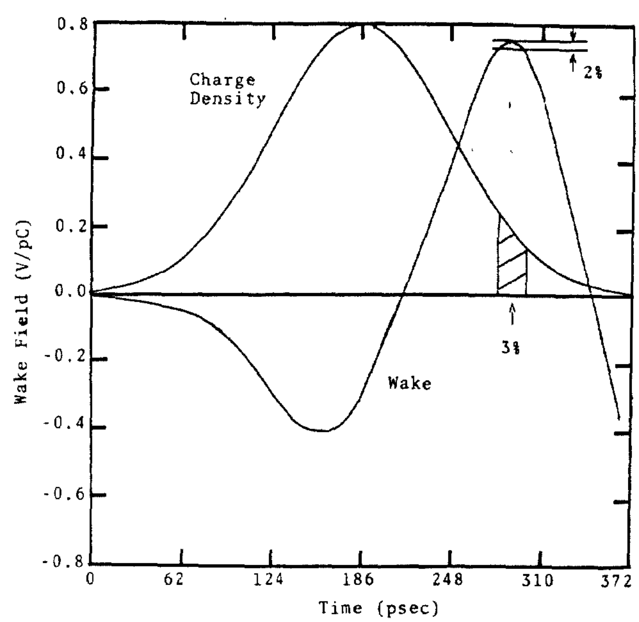

Fig. 3 Longitudinal wake potential for one cell. Gaussian bunch length is 1.85 cm.

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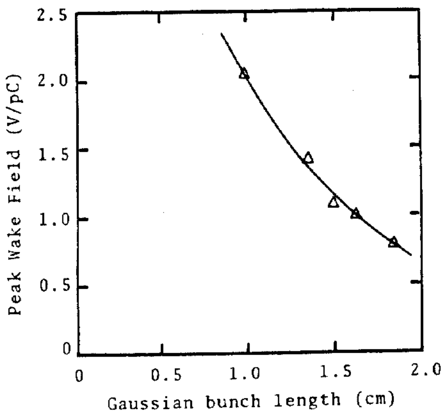

Fig. 4 Peak wake potential versus bunch length.

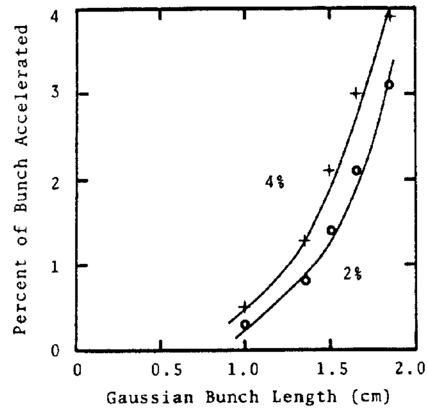

Fig. 5 Fraction of charge accelerated within 2% and 4% of the maximum vs σ_τ.

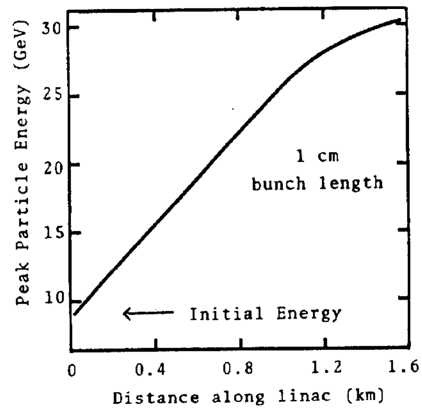

Fig. 6 Peak particle energy versus distance. The gradient is 16 MV/m.

for a CED linac.[4] The cavity shown in Fig. 1 is one of the simpler designs. It is symmetric about the beam line and has a one centimeter beam hole determined by optics. The cavity construction is inexpensive being made of spacers and washers with an attached center tube alternately placed inside a vacuum tube. The charge density and the single cell wake potential for a 1 cm Gaussian bunch are shown in Fig. 2. The center of the bunch is decelerated by 1 V/pC per cell, and the tail is accelerated by about 2 V/pC per cell. The cavity rings after the bunch passes with a peak field of about 2 V/pC, allowing acceleration of low intensity, trailing bunches properly phased. The wake potential for a 1.85 cm bunch passing through the same cell is shown in Fig. 3. Note that the peak acceleration is lower but that it occurs higher on the Gaussian density distribution so more particles are accelerated.

The peak acceleration of the wake potential has been calculated for several other bunch lengths and all are plotted in Fig. 4. The maximum wake falls rapidly with bunch length. Conversely, the fraction of the initial charge distribution which is near the peak acceleration increases sharply with bunch length. The fraction which is accelerated within 2% and 4% of the maximum is plotted versus bunch length in Fig. 5. Therefore, if the bunch can be made more intense for a given cavity design, the bunch can be lengthened to restore the gradient and more charge is accelerated. The gain is very rapid because not only does the fraction near the peak acceleration increase but the total number of particles increases. The ratio of the peak acceleration to peak deceleration in the bunch is very important because it determines the peak particle energy before the density distribution deteriorates from particle losses. For Gaussian bunches the results from BCI show that this ratio does not exceed a value of two.

Energy Gain in a CED Linac

For example, suppose 10^{12} electrons with a bunch length of 1 cm are launched down a series of cavities shown in Fig. 1. The peak acceleration of any particle is 16 MV/m and the peak deceleration is 8 MV/m. If the initial energy is 9 GeV, then after 1000 m the most accelerated particle is at 25 GeV and the most decelerated particle is at 1 GeV. Assuming a 1 GeV cutoff in the linac optics, particles start to be lost after 1000 m. As the charge distribution is changed, the wake field can be calculated using an approximate Green's function calculated for the cavity using a very short bunch. It is used to perform a convolution integral over the existing distribution to give the total wake potential. A calculation for this example[4] shows that the peak acceleration declines sharply after 1100 m. Fig. 6 shows the peak energy versus distance along the linac using the proper distribution and wake at each cavity. 30 GeV is passed at 1500m.

Magnetic Lattice

A strong focusing FODO lattice is suitable to maintain the small transverse dimensions of the beam in a CED linac. Such a lattice contains quadrupoles of focal length f separated by drift lengths L. There is no dispersion. The maximum value of the beta function in a period is plotted versus 1/f for various period lengths in Fig. 7. The choice of the period and focal length must be made so that the entire energy spectrum of the beam can remain within the linac acceptance. Near

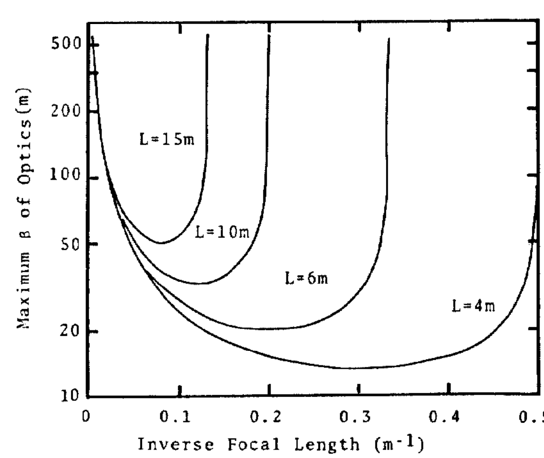

Fig. 7 Maximum beta of the beam in a CED linac vs 1/f. f is the quadrupole focal length and L the spacing.

Table I Parameters of a 30 GeV Accelerator

CED Linac:	
Energy (E_0)	30 GeV
Minimum invariant emittance	1×10^{-4} rad-m
Repetition rate	12 Hz
e^+/e^- per cycle (+-0.6% of E_0)	10^9 / 3×10^9
Linac length	1500 m
Driver bunch intensity	1×10^{12}
Driver bunch energy	9 GeV
Driver bunch length (σ)	1.0 cm
Accelerating gradient	16 MV/m
Electron Accumulator:	
Circumference	725 m
Energy loss per turn	5.8 MeV
Transverse damping time	7.5 msec
Number of bunches	4
Final emittance	0.85×10^{-4} rad-m

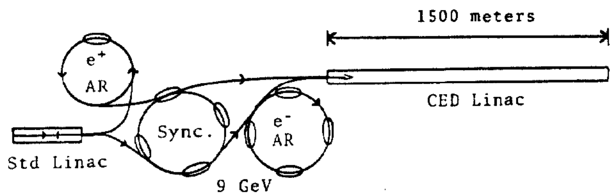

Fig. 8 30 GeV e^+-e^- CED linac accelerator

the beginning of a CED linac the quadrupole spacing can be large because the energy spread is small, but at the end the spacing must be shortened to four to six meters to allow both high and low energy particles to pass. This determines the low energy cutoff (about 1 GeV).

Transverse Wake Potentials

Transverse wake potentials[6,7] can cause emittance growth and particle losses. These wakes are currently under study and not covered here except to note that there are many features of CED linacs which reduce their effects. The wide range of particle energies (approaching 100%) causes strong Landau damping. Proper cavity design can reduce these potentials. The bunch length and intensity can be freely chosen. Careful design of the optics can keep the beam sizes small where the transverse forces are the most severe. Finally, the initial particle energies are quite high.

30 GeV Electron/Positron Accelerator

A 30 GeV accelerator consists of a 1500 m CED linac driven by a 9 GeV electron accumulator, a synchrotron, a 1 GeV positron accumulator, and a 1 GeV standard linac. See Fig. 8 and Table I. A 60 Hz linac produces eight electron bunches (5×10^{10}/bunch) using a gun like that designed for the SLAC SLC[8]. Four bunches make positrons and four are accumulated at 9 GeV. Twelve times per second 10^{12} electrons and 10^{10} positrons are produced and injected into the CED linac. The energy gain versus distance is shown in Fig. 6. With reasonable efficiencies 10^{12} electrons and 7×10^{11} positrons per minute can be produced at 30 GeV with an energy spread of +/-0.6%.

110 GeV Electron-Positron Collider

This collider is two CED linacs aimed at one interaction region. See Fig. 9 and Table II. Each linac has five subsections. Each sub-

Table II Parameters of a 110 GeV Collider

Luminosity including disruption	6×10^{29} cm^{-2}s^{-1}
Energy per beam	110 GeV
Number of particle per beam	$\sim 3 \times 10^{10}$
Repetition rate	24 Hz
Invariant emittance ($\epsilon\gamma$)	5×10^{-5} rad-m
Beam size ($\sigma_x = \sigma_y$)	1 μm
Equivalent beta function	5 mm
Energy spread	∿1%
Number of linac sections / beam	5
Linac section length	1500 m
Driver bunch intensity	1×10^{12}
Driver bunch energy	9 GeV
Driver bunch length	1.0 cm
Energy gain per section	21 GeV
Special acc. ring energy	7.5 GeV
Special acc. ring inv. emit.	4.9×10^{-5} rad-m

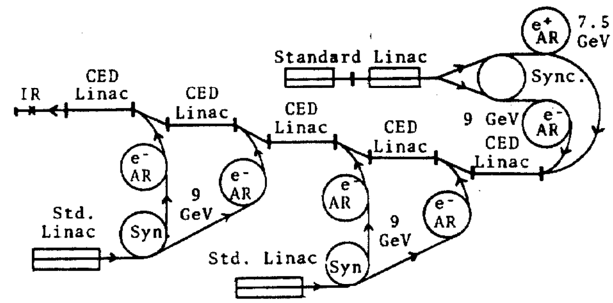

Fig. 9 110 GeV per beam e^+-e^- collider.

section is driven by a 9 GeV electron accumulator, a synchrotron, and a standard linac. In addition, a low intensity, low emittance electron or positron bunch is produced in a special 7.5 GeV accumulator which feeds into the first subsection. This special bunch is carefully passed through all the subsections and ultimately collides at high energy. It is accelerated by the other larger bunches. Two adjacent subsections are joined with a non-dispersive translation section which allows the injection and ejection of driver bunches and the passage of the low intensity bunch. Assuming the conditions in Table II and a $\beta^*_{x,y}$ of 5 mm similar to the SLAC SLC[9], the luminosity is 2×10^{29} cm^{-2}sec^{-1}. The disruption[10] has a value of about 1 and enhances the luminosity by a factor of 3 to 6×10^{29} cm^{-2}sec^{-1}. The luminosity can further be enhanced by accelerating several bunches per cycle.

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References

1. T. Weiland, XI Int. Conf. on Accel. (1980).
2. E. Perevedentsev and A. Skrinski, II ICFA Workshop on Accel. CERN 1979.
3. M. Friedman, PRL 31-18, p. 1107 (1973).
4. J. Seeman, CBN 82-17, Cornell, May 1982.
5. T. Weiland, DESY 81-088, December 1981.
6. T. Weiland, DESY 82-015, March 1982.
7. G. Aharonian, et.al., CLNS 82/535, Cornell.
8. J. Clendenin, et.al., SLAC-PUB-2828.
9. B. Richter, SLAC-PUB-2854.
10. R. Hollebeck, SLAC-PUB-2535.