An Injector Complex for the Main Beams of the CERN Linear Collider

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Abstract

A power efficient scheme is proposed for the injector complex of the main beams of the CERN Linear Collider (CLIC). It fulfills all the beam parameter specifications required for a high luminosity, mainly a high particle production rate, specially for the positrons (6 10^{13} e^+/sec), in very small normalized RMS emittances (1.5 10^{-6} rad m in horizontal, 5 10^{-8} rad m in vertical) and bunch lengths (170 µm) at a high repetition rate (1.7 kHz). The injector complex is based on two superconducting linacs with recirculations of the CEBAF type, accelerating the primary electron beam for positron production as well as the electron and positron main beams in a pulse-to-pulse modulation mode up to the 9 GeV/c energy required at injection into the main linacs. After description of the operational aspects, the main elements constituting the injector complex are treated: particle production and acceleration, damping rings and bunch compressors. Finally, a rough evaluation of the cost and power consumption of such a complex is given.

1. Introduction

In the frame of R and D for a possible future electron-positron collider at an energy of 500 GeV to 2 TeV in the centre of mass, the technical feasibility of a scheme based on high frequency accelerating structures at 30 GHz powered from a high intensity drive beam [1] is underway at CERN. The aim of the injector complex of the CERN Linear Collider (CLIC) is to prepare and provide both electron and positron main beams as required at injection into the main linacs. As for any Linear Collider, the design of the injector complex is very challenging because of the extremely small transverse and longitudinal emittances required for a high luminosity at the Interaction Point. In the case of CLIC, it is specially critical because of the very high repetition frequency which necessitates a large production of particles (specially for the positrons: 6 10^{13} e^+/sec) and a fast damping rate. An injector complex based on conventional technology using room temperature accelerating structures at the standard frequency of 3 GHz had already been envisaged [2]. But because of the high repetition frequency of CLIC and the strong fields in the accelerating sections necessitated by the heavy beam loading from the primary beam for positron production, the RF power dissipated in the sections was excessive and required a large number of powerful stations of modulators and klystrons. A new scheme (fig. 1) based on superconducting linacs with recirculations, well adapted to a high repetition process, is proposed which strongly reduces the overall RF and wall plug power consumptions. It is matched to the new beam requirements [3] at injection into the main linacs taking into account realistic beam transmission all along the injector complex as well as transverse blow-up induced by the strong wake fields during acceleration in the main linacs at the specially high frequency of 30 GHz.

Number of bunches in the train:	k = 1 to 4
Number of particles per bunch :	Nb = 8.3 10^9 $e^\pm$
Minimum time separation between bunches:	Δ = 800 psec
Train repetition frequency:	fr = 1.7 kHz
Normalized horizontal emittance:	ε_x^* = 1.5 10^{-6} rad-m
Normalized vertical emittance:	ε_y^* 5 10^{-8} rad-m
RMS Bunch length:	σ_z = 170 µm
Injection Energy into the main Linac:	E = 9 GeV

2. Description of the Scheme

The two beams, of electrons and positrons, are provided by the same facility every CLIC repetition period

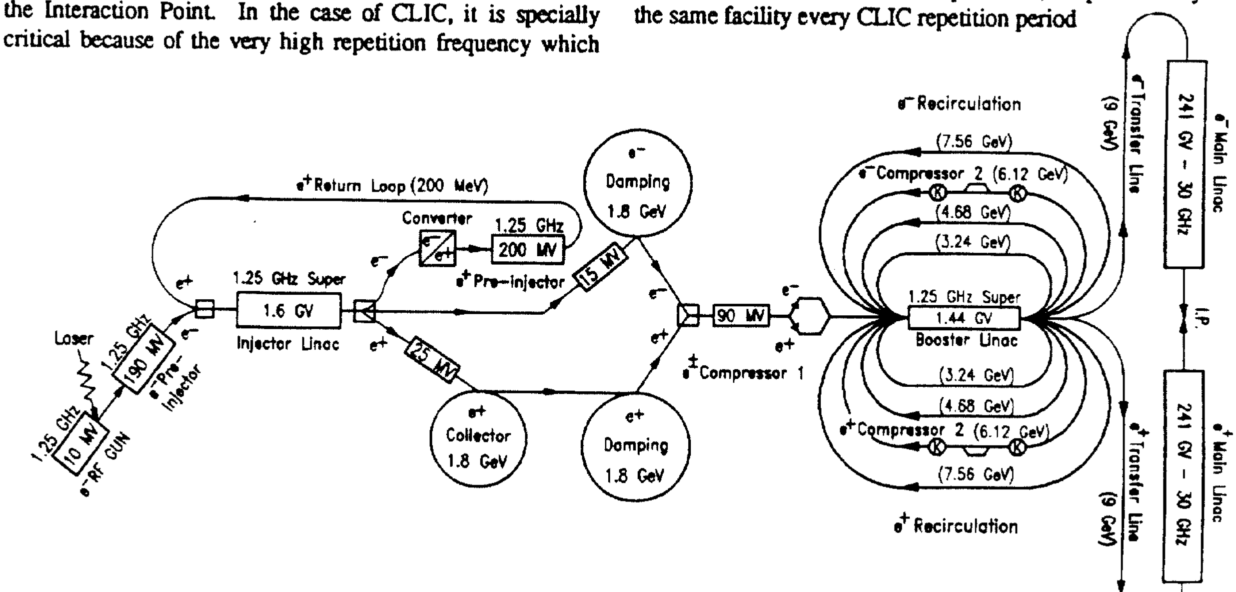

Fig. 1: Layout of the Injector Complex for the e^+ and e^- CLIC Main Beams (not to scale)

(588 μsec) by pulsing a few elements alternating regularly from the electron to the positron mode of operation. The evolution of the beam parameters all along the injector complex is summarized for both the electron and the positron beams in table 1. Although the CLIC scheme is working nominally with a single bunch, the whole complex is dimensioned for the more demanding option of multibunches with 4 bunches separated by 800 psec. This time delay is extremely important as it determines the minimum RF frequency of 1.25 GHz compatible with the bunch intervals and usable in the whole complex. Every RF structure is made superconducting at 1.25 GHz with a continuous RF feeding to compensate for the (low) losses on the wall and for the power taken by acceleration of the beams (fig. 2). Taking advantage of the vigorous R and D effort engaged in the TESLA project on structures at a similar frequency [4], as high as possible but realistic accelerating fields of 10 MV/m are assumed. A large stored energy is favorable for beam loading induced by the high intensity primary electron beam for positron production in the injector linac and by the recirculations in the booster linac.

Table 1: Evolution of the main beam parameters along the Injector Complex (in RMS values at the exit of each system)

	E (GeV)	N_b/bunch (10^9 $e^{\pm}$)	σ_z (mm)	$\gamma\epsilon_x/\gamma\epsilon_y$ (10^{-6} rad-m)
Electrons				
RF Gun	0	20.0	1.0	30/5
Pre-Injector	0.2	17.9	1.3	40/5.5
Injector	1.8	16.1	1.5	50/6.0
Damping Ring	1.8	12.9	2.1	1.3/0.03
Compressor 1	1.8	11.6	1.0	1.35/0.035
Compressor 2	6.1	9.3	0.15	1.45/0.040
Booster	9.0	8.3	0.16	1.5/0.05
Main Linac	250	6.0	0.17	1.8/0.20
Positrons				
RF Gun	0	90	1.0	100/100
e^- Pre-Injector	0.2	72	1.3	150/250
e^- Injector	1.8	62	1.5	200/200
Converter	0	25	3.0	9000/9000
e^+ Pre-Injector	0.2	22	3.5	9500/9500
e^+ Injector	1.8	20	4.0	10000/10000
Collector Ring	1.8	16	2.1	50/5
Damping Ring	1.8	13	2.1	1.3/0.03
Compressor 1	1.8	12	1.0	1.35/0.035
Compressor 2	6.1	9.3	0.15	1.45/0.40
Booster	9.0	8.3	0.16	1.5/0.05
Main Linac	250	6.0	0.17	1.8/0.20

Electron Operation:

The train of bunches produced by an RF gun with a photocathode illuminated by a laser is accelerated to 1.8 GeV by a 200 MeV pre-injector followed by a 1.6 GeV injector linac. It is then injected into a damping ring with a 283 m circumference specially designed for small equilibrium emittances and short damping times [5]. A special mode of injection/extraction with closed orbit deformations modulated from train to train by RF transverse deflectors [6] allows to store up to 76 trains in the ring such that each train is damped for 4 damping times to the requested transverse emittances (fig. 3a). After extraction, the length of the bunches is reduced to the specified value in two stages of magnetic bunch compression following the introduction by an RF cavity at zero phase of a momentum to phase correlation along the bunches [7]. The train of bunches is finally accelerated to 9 GeV by a 1.44 GeV booster linac and transferred to the entry of the main linac via a 3 km long transfer line and a 180° isochronous bend in the same tunnel as the main linac. For sake of economy of superconducting RF structures, this linac is equipped with 4 isochronous recirculations arcs similar to CEBAF [8].

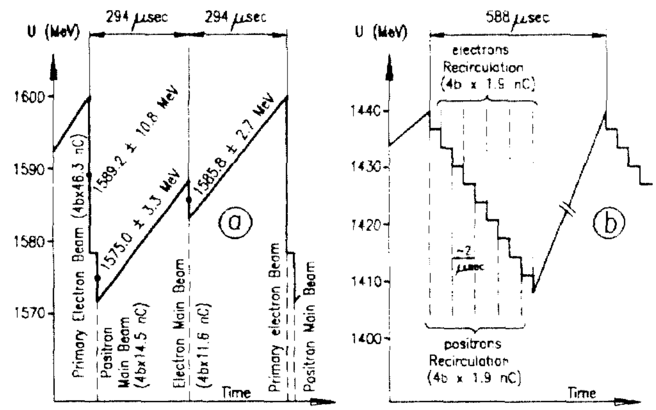

Fig. 2: Compensation of beam loading in the injector (a) and in the booster (b) linacs:

$$\frac{dU}{U} = -\frac{\omega_{RF} r_o'}{2E} = -2.9 \cdot 10^{-4} q(nc)$$

Positron Operation:

Half a CLIC repetition period later, the injector complex is switched from the electron to the positron mode of operation by pulsing two elements only: the electron gun intensity and the bending magnet at the exit of the injector linac. A high charge per bunch generated by the RF gun is accelerated by the pre-injector and injector linacs to 1.8 GeV and sent on a positron converter for positron generation. The positrons are captured and recirculated at 200 MeV to the beginning of the injector linac in a similar way as in the SLC [9]. After acceleration to 1.8 GeV by the injector linac, the positron beam is first pre-damped (fig. 3b) in a collector ring with large transverse and longitudinal acceptances then damped in a damping ring similar to the one used for the electrons. The positron beam is finally accelerated to 9 GeV and transferred to the positron main linac as for the electrons.

3. Positron Production

The positron production and capture is based on the standard technology of an electromagnetic shower initiated by a primary electron beam in a thick target followed by a flux concentrator and high gradient accelerating section as successfully developed on the SLC but with an effective e^- to e^+ conversion yield (η = 0.225 e^+/e^-/GeV) improved by a factor 3. Following the SLC experience [10], such an improvement is possible if the acceptances along the whole chain of positron capture and collection are increased by at least a factor two in both transverse planes and 50% in the longitudinal plane. This is made possible by the large acceptances provided by the L band injector linac and by the addition of a collector ring prior to the damping ring with "normalized" transverse acceptances of:

$$A^*_x = A^*_y = 0.1 \text{ rad-m}$$

With such a yield, the positron charge per bunch, N_b^+, is created by a primary electron beam with a reasonable charge per bunch, N_b^-, of:

$$N_b^- = N_b^+/\eta * E^- = 6.2\ 10^{10} e^-$$

and a primary beam energy, E^-, of 1.8 GeV as provided by the injector linac.

This corresponds to an energy density on the target of:

$$\rho = k * N_b^- * E^-/(\pi * \sigma^2) = 1.4\ 10^{11}\ e^- * \text{GeV/mm}^2$$

well below the experimental limit of $2\ 10^{12}\ e^- *$ GeV/mm^2 as found at SLC even in the multibunch option (k = 4) if the RMS beam radius on the target is made larger than σ = 1 mm.

In spite of the high repetition frequency of the positron production, the average beam power, Pb, does not exceed the power presently deposited on the SLC target (47 kWatts), at least in the nominal single bunch option:

$$Pb = k * N^- * E^- * fr = 31 \text{ kWatts (with k = 1 bunch)}$$

In the case of multibunches, the power dissipation on the target would have to be improved by a factor 2.6 which seems feasible.

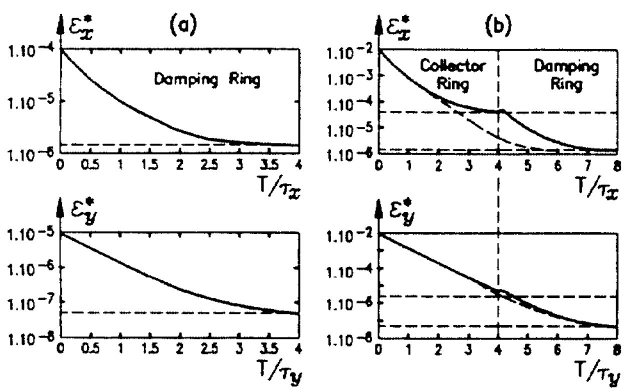

Fig. 3: Damping of the normalized transverse emittances of the electron (a) and positron (b) beams as a function of the circulating time, T, normalized to the damping time, $\tau_{x,y}$.

4. Cost and Wall Plug Power Estimations

As shown on table 2 below, the main contribution to the overall cost and power consumption of the whole complex comes from the superconducting linac structures of the TESLA type with a total length of 340 m. An average cost of 300 kFrs/m including structures, RF power and cryogeny has been assumed, a value in between the one spent on LEP200 for structures at a lower frequency and the one aimed at in the TESLA study. Because of the high efficiency of the superconducting structures, the total RF power, Prf = 974 kW, corresponds nearly to the power taken by the beam for acceleration. The cryogenic power to be installed, Pc = 9.5 MW, is the necessary power to compensate for the static and dynamic losses on the structures (17 kW) at a 4 K operation, assuming a 2.10^{-3} cryogenic power efficiency.

Table 2: Rough estimate of the cost and wall plug power consumption of the injector complex.

	Power (MWatts)	Cost (MFrs)
Electron Source and Bunching	0.2	1
Superconducting Linacs (340 m)	10.6	100
Positron Production and Capture	0.5	2
Positron Collector Ring	1.5	10
Elec. and Positron Damping Rings	4.0	50
Recirculation Loops	2.5	12
Transport Lines (9 GeV)	3.0	10
Bunch Compressors	1.5	15
Civil Engineering Infrastructures	1.5	50
Total	25 MWatts	250 MFrs

5. Conclusion

An injector complex for the main beam of CLIC which fulfills all the required parameters for a high luminosity can be built with standard technology. Beam acceleration with superconducting structures in L band and recirculation arcs of the CEBAF type are well adapted to the high repetition rate of the scheme and provide comfortable acceptances favorable to positron capture, as well as high stored energy beneficial to beam loading. The overall cost and wall plug power are both dominated by the superconducting structures and would profit for any improvement from the vigorous R and D effort already engaged in the TESLA study.

6. Acknowledgments

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7. References

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