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I. Introduction

The demand for e^+e^- collisions beyond the LEP 200 energy range up to the Multi TeV region requires the development of linear collider technology and there seems to be international agreement today, that the first step should be a 2×250 GeV linear collider (see for example [1]). Different studies around the world concentrate on different designs, all based on partially or non developed technology. The general differences have been discussed in many Linear Collider workshops and have been presented in numerous overview talks. The fundamental difference so far is the operating frequency of the main linac which varies for the studies (TESLA, SBLC, NLC, JLC, VLEPP, CLIC) between 1.3 and 30 GHz. Based on a number of arguments [2] which mainly summarise the availability, the cost optimisation and the experience gained so far with S-Band technology, a 500 GeV S-Band linear collider design has been worked out at DESY [3].

More recently, the only study group working on a two beam scheme with the highest frequency option for the collider beam (CLIC, a linear collider study at CERN in collaboration with people from SLAC), has reviewed the design of the main drive beam leading to a more reasonable and very efficient design [4]. Although a lot of R&D, which will require money and time, will have to be done to fully develop the required 30 GHz technology for such a high frequency linear collider, the general idea seems interesting enough to explore possibilities a little different from the presented CLIC scheme. For example, a low frequency linac proposed so far as a linear collider, could later on in principle be reused as a driver linac. Especially this idea will be applied to the S-Band Linear Collider.

The basis of the optimisation is, that the 33 km long tunnel, fully equipped with an S-Band collider exists and that as much hardware as possible should be reused without any modification. As a result it will be shown that a 3 TeV Linear Collider, based on 30 GHz technology and powered by an S-Band linac seems a reasonable, power efficient and cost effective upgrade path from a 0.5-1 TeV S-Band collider to a 3 TeV collider.

II.Short Review of the S-Band Linear Collider Concept

A linear collider consists of two opposing linear accelerators, one accelerating positrons, the other electrons. From the technical parameters of the proposed S-Band linear collider [3] it can be seen that from today's point of view the operating conditions are close to what has been achieved already. Possibilities for upgrading to a certain extent have been discussed as well in this report, but seem to be limited to approximately 1.3 TeV with a luminosity barely reaching 1×10^{34} [1/cm^{2}sec] in a tunnel with a total length of 33 km.

Active length	30.2	km
$t_{beam\ pulse}$	2	μs
n_b/pulse	125	
Δt_b	16	ns
f_{rep}	50	Hz
$\varepsilon_x/\varepsilon_y$	10/0.5	10^{-6} m
β_x^*/β_y^*	22/0.8	mm
σ_x^*/σ_y^*	670/28	nm
σ_z	0.5	mm
$\langle\Delta E/E\rangle_{rad}$	3.2	%
P_b	2 x 7.2	MW
P_{AC} (2 Linacs)	139	MW
L (incl H_D)	3.75	10^{33}cm^{-2} s^{-1}

Table 1 Main parameters of the S-band 500 GeV (c.m.) linear collider.

III.General Description of the Two Beam Accelerator

For a better understanding of the boundary conditions, a short description of the CLIC two beam accelerator scheme will be given. The parameters and picture are taken from [4] and [6] respectively.

In a two beam accelerator, the high power rf for the main linac operating at 30 GHz is produced by a low energy beam, typically one up to a few GeV, with a high beam current. The rf is excited in transfer structures, which interact with the high current beam and finally after being deaccelerated to almost 1/10 of the start energy or so, this beam is dumped. In order to fill and accelerate bunch trains in a 30 GHz structure, comparatively short rf pulses, asking for short current pulses with kilo-amperes of pulse current. Such high pulse current could either be produced directly, for example with laser driven high charge rf guns, or using beam pulse compression techniques as being described in [4]. The latter is the basis of the most recent ideas. A number of short beam pulses is produced from a long lower current (few amperes) linac pulse, produced by a conventional highly loaded and therefore very efficient normal conducting linac. While the compression is done in various steps and in various compressor rings, the total drive beam pulse length does not change and is given by the counter-flow feeding of the transfer structures with the drive beam pulses. The principle is sketched in figure 3 with the proposed CLIC scheme as an example. A 1.16 GeV, 8.8 kA linac operating at 937 MHz is situated close to the interaction point together with the required compressor rings. After compressing always pieces of the drive beam pulse by a factor of ≈30, they are send towards the beginning of the main linacs and subsequently fed into the transfer structures. This scheme automatically determines the length of the drive beam pulse which is: $t_{db}=2L_{linac}/c$.

Giving the constraint of the total tunnel length of 33 km and assuming the efficiency for rf to beam power conversion at 30 GHz (= 27 %) as well as the drive beam to rf conversion in the transfer structure (= 67 %) given by the CLIC study team, two beam accelerators seem to be a possibility to achieve 3 TeV and higher center of mass collisions with a total power consumption for rf generation (at 30 GHz) of less than 200 MW. Again, after having learned how to operate a 500 GeV cms linear collider with larger spot size, more relaxed tolerances and more standard technology, on a future time scale the two beam approach seems reasonable. The transition point (in time), going from collider operation to two beam operation in addition is rather flexible, because the S-Band Linac can reasonably be upgraded to roughly 1.3 TeV before it is limited in energy, Luminosity, beam power and average power (>250 MW AC power).

In order to transform the S-Band Linear Collider linac into a driver linac for a two beam accelerator the cheapest possible transformation from a high energy linac with high gradient and comparatively small beam current to a low energy, highly efficient, large pulse current, S-Band linac has to be investigated.

IV. Assumptions, Basic Parameters, Constraints and Optimisation

In order not to go to much into details and profit as much as possible from the work being done already, we will make a number of asumptions which mainly have to do with the study work being done on CLIC already:

1. We will assume a 30 GHz main linac like in the CLIC study [4].
2. We will assume an rf to beam efficiency like CLIC for the high energy 30 GHz accelerator (27 %).
3. We will assume a transfer efficiency for the drive beam to rf power at 30 GHz similar to the CLIC study (67 %).
4. As a first step, we will try to produce a drive beam bunch train similar to the one used in the CLIC study [4]

1. Assumptions

The main parameters of the CLIC study which are of further interest for the presentation of the paper are given in the next table.

High Energy Beam Parameters		
E_{cms}	3	TeV
Ne	0.64	nC
Nb	150	
f_{rep}	75	Hz
$\eta_{rf\ to\ beam}$	27	%
$T_{beam\ pulse}$	120	nsec
Power Conversion		
High Energy Electron beam energy per pulse	144	kJ/pulse
High Energy beam peak power	1.2	TW
RF Energy per pulse	≈540	kJ
Total RF Peak Power required at the structure	4.5	TW
Average Power (75 Hz):		
high energy beam	11	MW
RF power	40	MW
Drive Beam (67 % efficiency)		
for both linacs	≈ 800	kJ/pulse
average beam power	≈ 60	MW

Table 2 Main parameters of the High Energy beam used in the CLIC study[4].*

2. Basic Formulas

The basic formulas to optimise the design of an S-Band Linac utilised for high current operation are given below. In our nomenclature τ being the total attenuation in each of the structures, **P** the rf peak power going into the structure, **L** the structure length, r_{sh} the shunt impedance of the structure per meter and **i** the beam current.

First the total accelerating voltage of the loaded structure:

$$V_{tot} = \sqrt{1-e^{-2\tau}} \cdot \sqrt{P \cdot r_{sh} \cdot L} - \frac{i \cdot r_{sh} \cdot L}{2} \cdot \left[1 - \frac{2\tau \cdot e^{-2\tau}}{1-e^{-2\tau}}\right] \quad (1)$$

The total voltage is decreasing proportional to the beam current and increasing with the square root of the peak power going into the structure.

$$(2)\quad \eta_{max} = \frac{1}{2} \cdot \left[\frac{\left(1-e^{-2\tau}\right)}{\left(1-e^{-2\tau}\right)-\left(2\tau \cdot e^{-2\tau}\right)}\right]$$

The transfer efficiency is only determined by the total attenuation of the structure.

$$(3)\quad \begin{aligned} i_{\eta\ max} &= 2 \cdot \sqrt{\frac{P}{r_{sh} \cdot L}} \cdot \eta_{max} \cdot \frac{1}{\sqrt{1-e^{-2\tau}}} \\ i_{\eta\ max} &= \sqrt{\frac{P}{r_{sh} \cdot L}} \cdot \left[\frac{\left(1-e^{-2\tau}\right)^{1.5}}{\left(1-e^{-2\tau}\right)-\left(2\tau \cdot e^{-2\tau}\right)}\right] \end{aligned}$$

The current for maximum transfer efficiency is defined by the current which loads the structure up to the point where no rf power is coming out of the section. In this case all the power is partially transferred to the structure to generate the accelerating field and all the rest is transferred to the beam. In a truly constant gradient structure this is always the case if the loaded gradient is half of the unloaded gradient. The optimum current now depends on the attenuation, the available peak power, the shunt impedance and the active length of the linac. All of the parameters will be used for optimization later on.

$$(4)\quad E_{db} = I_{db} \cdot V_{tot} \cdot t_{db}$$

the energy per pulse in the drive beam (db) required to drive the transfer structures with the 30 GHz rf. The drive beam pulse length t_{db} is already fixed. It is: $t_{db}=2L_{linac}/c$, where L_{linac} is the one linac length (15 km) and c the velocity of light (compare [4]).

* The authors are indebted to R. Ruth from SLAC who presented the ideas and the parameters at DESY on July 7th 1998 at DESY.

$$(5) \qquad vg(z) = \frac{\omega \cdot L}{Q} \cdot \frac{\left(1 - z/L\right)\left(1 - e^{-2\tau}\right)}{1 - e^{-2\tau}}$$

the group velocity at the beginning and at the end of the constant gradient structure which, has some impact on the achievable shunt impedance and therefore should be mentioned.

For illustration the structure efficiency and the optimum current for maximum efficiency are plotted versus the attenuation. The parameters assumed for optimum current are a shunt impedance of 30 MΩ/m, a peak power of 75 MW per structure and a length of 4 meter.

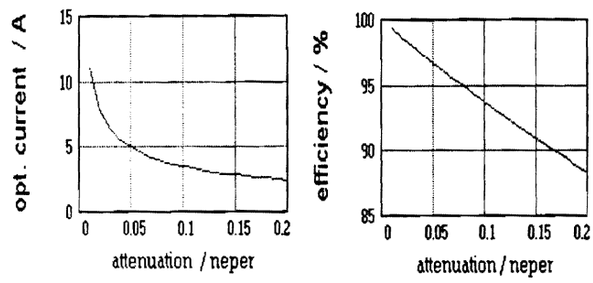

Figure 1 Structure efficiency and optimum current for maximum efficiency versus the attenuation of the structure. R_{sh}= MΩ/m, P=75 MW, L=4 m.

3. Constraints from the Linear Accelerator Set-Up for Collider Operation

The general rule for optimisation is, to use as much of the existing hardware as possible without any changes.

a) Modulators and klystrons are operating with a pulse length of 3 μsec. In order to achieve a beam pulse length of $t_{db}=2L_{linac}/c=100$ μsec each linac has to be divided into 33 subsections, delivering a 3 μsec long beam pulse stacked together in a transport line running parallel to the linac. Each subsection would have a **maximum** number of 35 klystrons available

b) For the installed accelerating structure, which is used in the collider mode, it becomes immediately clear, that it can not be used for highly efficient operation. In order to achieve maximum transfer efficiency, the attenuation τ has to be as small as possible (see (2)), which is in contradiction to high gradient operation as being required for the linear collider mode. For the installed collider structure the maximum efficiency is 42 % with an optimum beam current of 860 mA only. Additionally it would be impossible to run amperes of current through the structure without enormous transverse excitation of the beam (Beam Break Up instability). Therefore the structure would have to be exchanged.

c) The choice of the accelerating (loaded) gradient and the current in the beam pulse to a certain extent is arbitrary. Beam stability mainly determines these parameters and they can finally be fixed only after simulating the beam behaviour with tracking programs.

4. Optimisation of the Parameters

In order to achieve maximum transfer efficiency, τ has to be as small as possible. From formula (2) it can be seen that the transfer efficiency η approaches 1 if τ approaches 0. At the same time the optimum current (compare formula (3)) approaches infinity and constraint number c) limits the choice of τ. In addition smaller values for the attenuation τ lead to a higher group velocity automatically (5) resulting in larger iris diameters. As a consequence the shunt impedance $\mathbf{r_{sh}}$ is dramatically decreased. To make full use of the available peak power, **P** in equation (3) is given by the existing installation which has a 150 MW klystron per twelve meter of tunnel. The shunt impedance is more or less given by the frequency in a 2π/3 mode structure as well as by the group velocity, and only the length **L** is left to balance the attenuation τ and therefore limit the optimum current (see equ. (3)) at which the maximum transfer efficiency is achieved. Later on we will see that in our case this results in a comparatively long accelerating structure.

V. Comparison to the CLIC Study and Results

For direct comparison with the CLIC study, where an optimised driver linac at 0.987 GHz has been

used to generate the drive beam, we assume a total energy of 800 kJ per drive beam pulse (400 kJ per linac) operating with a repetition rate of 75 Hz (compare **table 2**).In addition a parameter list which better fits the installed hard ware in the tunnel of the S-Band Collider will be presented. The main difference is the 50 Hz operation instead of the 75 Hz, which is the standard assumed in the Linear Collider study[3].

Drive Beam Linac Parameters (75 Hz)		
nr of 150 MW klystrons	30	
total rf power at input[1]	4200	MW
shunt impedance [2]	30	MΩ/m
attenuation	0.06	neper
length of the structure[3]	4	m
group vel. vg(0) – vg(L)	16-14	% c
unloaded gradient	7.7	MV/m
structure efficiency η	96	%
filling time	86	nsec
Power Conversion		
current per pulse	4.3	A
loaded energy of the linac	0.94	GeV
beam peak power	4.04	GW
loaded gradient	3.92	MV/m
current pulse length	3	μsec
efficiency of the modulator	70	%
efficiency of the klystron	50	%
Efficiencies		
ave. rf power at 3 GHz[4]	67	MW
AC line power[5]	192	MW

Table 3 Main parameters of one of the 2x33 subsections of the drive beam linac for direct comparison with the CLIC study (f_{rep}=75 Hz operation)

In both cases a comparatively conservative efficiency for the modulator (70 % for AC to high voltage DC) and the klystron (50 % for DC beam to rf) is assumed. The two different parameter lists are presented in **table 3** and **table 4**. The overall efficiency which could be achieved for rf to beam power is in both cases larger than 95 % (96 % and 97 % respectively).

In the examples given in the two tables, always one of the 2x33 subsections of the driver linac are presented (compare section 3). The total length is less than 450 meters (=15 km/33) and the number of klystrons and modulators which are in principle available are ≈35.

Drive Beam Linac Parameters (50 Hz)		
nr of **185 MW** klystrons	35	
total rf power at input	6200	MW
shunt impedance	30	MΩ/m
attenuation	0.04	neper
length of the structure	4	m
group vel. vg(0) – vg(L)	24-22	% c
unloaded gradient	7.1	MV/m
structure efficiency η	97.4	%
filling time	57	nsec
Power Conversion		
current per pulse	6.0	A
loaded energy of the linac	1.0	GeV
beam peak power	6.0	GW
loaded gradient	3.57	MV/m
current pulse length	3	μsec
efficiency of the modulator	70	%
efficiency of the klystron	50	%
Efficiencies		
ave. rf power at 3 GHz	65	MW
AC line power	185	MW

Table 4 Main parameters of one of the 2x33 subsections of the drive beam linac optimised for the installed hardware in the tunnel (f_{rep}=50 Hz operation) . In this case the rf pulse at 30 GHz will have to be extended to compensate for the lower repetition rate.

VI.Differences to the Optimised CLIC Scheme

The main difference to the CLIC scheme is the difference in pulse length for the driver linac. The total beam pulse length which is determined by the counter-flow distribution of the drive beam bunches with respect to the main beam is given. For CLIC

[1] 10 MW losses are subtracted per klystron
[2] large group veocity has reduced shunt impedance
[3] two structures per klystron assumed similar to LC study
[4] Prf = 2 x 33 x 30 x 150MW x frep x t_{pulse}
[5] Pac = Prf / η_{mod} x $\eta_{klystron}$

one single L-Band linac produces the 92 μsec long train while in our case, it is formed by adding 33 3 μsec beam pulses together.

The operating frequency of the driver linac is higher by a factor of three. This leads to stronger wake-fields and the number of particles per bunch has to be reduced. The total current per drive beam linac is reduced by a factor of two compared to CLIC automatically because a drive beam linac is available in each tunnel. Finally the efficiency for rf to beam power can be made equal because there is no frequency dependence in equation (2) and (3). Only the shorter modulator pulse leads to a smaller overall efficiency because rise and fall times contribute more to the power bill.

Due to the higher frequency a totally different accelerating structure has to be used in order transfer the rf power to the beam. In table 3 and 4 the main parameters of the structure are already given. Smallest possible attenuation, high group velocity and following from that large iris diameter a small shunt impedance together with comparatively long structures, keep the optimum current for maximum efficiency around a few amps (compare eq. (3)). The iris diameter in our example is 60 mm (cavity diameter 86 mm) and the a/λ is 0.3. This has to be compared to an average iris diameter of 26 mm and an average a/λ of 0.13 for a high gradient structure. In addition, the iris thickness has been increased to 10 mm (instead of 5 mm). This geometry would make a hydro-formed structure, starting from a simple copper tube, very reasonable. In addition the very low accelerating gradient has low requirements on surface finish. Tolerances from the rf point of view are very uncritical because of the high group velocity of ≈25 % (strong coupling) and the extremely low power dissipation, which is roughly 100 Watt per meter. As a result, the only components which would have to be changed to transform the S-band linac into a driver linac, should become extremely cheap as compared to a standard accelerating structure. This is one of the strong points in favour of the scenario.

In addition the large iris will reduce the transverse and longitudinal wake-field (scales with the iris radius $a^{2.3}$ [5]). If strong damping really is necessary will have to be investigated, but because of the short beam pulse length and the comparatively short linac, requirements are definitely more relaxed.

VII. Injector Layout for the Drive Beam in the S-Band LC Tunnel

33 injectors per tunnel are required to produce a beam pulse with a total length of 100 μsec. Because of the large number, a simple and reliable layout must be found and a proposal can be found in this next section.

The capture gradient varies with the gun voltage. In order to capture the electrons right behind the gun, which avoids all kinds of sub-harmonic bunchers and additional hardware, and accelerate them up to relativistic energies a gradient of approximately 13 MeV/m over a length of 0.5 meter or so is required. The appropriate gun voltage is 250 kV. The dependence is shown in figure 2. The gun would be similar to a klystron gun with a control grid to modulate the intensity at the gun already and minimise beam loss in the structure. Due to the finite energy acceptance of the compressor rings of approximately 1 %, a bunch length in the linac of ± 8° or a sigma of < 1.2 mm is required. For an average pulse current of 6 A this means a peak current of 135 A (square distribution) or 1.3×10^{10} electrons per bunch.

The question is how much compression can one get from direct acceleration into a matched S-Band travelling wave buncher operating at a gradient of 13 MV/m in order to reduce the required peak current ?.

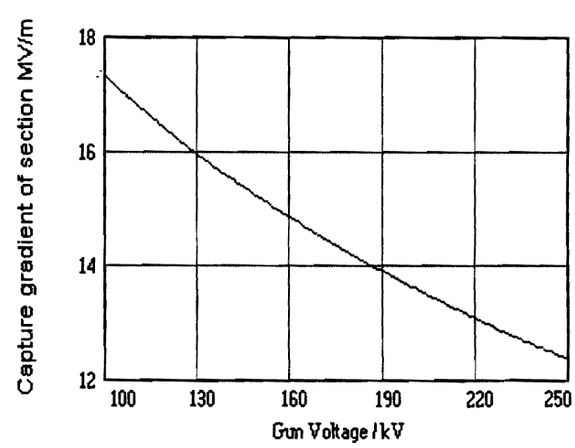

Figure 2 The capture gradient is shown as a function of the gun voltage. Optimum capture occurs for injection at +90° and final phase at 0° which is the crest of the wave.

With the well known formula for bunching (6) the acceptance into ± 8° of S-Band can easily be calculated.

$$\cos(\phi_\infty) = \cos(\phi_0) - \frac{2\pi}{\alpha} \cdot \left(\frac{1-\beta}{1+\beta}\right)^{0.5}$$
$$\alpha = \frac{e \cdot E_{acc} \cdot \lambda}{mc^2} \qquad (6)$$

where ϕ_∞ is the asymptotic phase angle and ϕ_0 is the injection phase. E_{acc} the accelerating gradient, λ the wavelength and β the velocity over c. For matched conditions (E_{acc} matched to gun voltage; Ugun ⇔ Eacc; 250 kV⇔13 MeV/m; second term in equation (6) equal 1) ± 30° would be captured into ϕ_∞ +8°. Therefore the peak current delivered from the gun would have to be 360°/60°*6 A which is 36 A and seems very reasonable, keeping in mind that the emittance could be comparatively large (> $1*10^{-5}$ π m rad (=γε)). Finally the allowed emittance has to be determined by tracking calculations, because during de-acceleration the emittance adiabatically increases.

VIII. The Kickers and the Transfer Line

Another cost driving term is the transfer line and the kickers running parallel to the linac to transport the beam pulse to the compressor ring. As a part of the beam line, where the 3 μsec long pulses are added together one after another to produce the 100 μsec long pulse, quadrupoles, corrector magnets, beam position monitors and a vacuum system are required. A sketch of such a beam line with three 280 meter long linacs is shown in figure 3.

With an expected emittance of 5×10-5 π*m*rad from the injector a quadrupole every 300 meters or so has to be installed, which leads to approximately 250 magnets, 33 kickers and 33 injectors required in total.

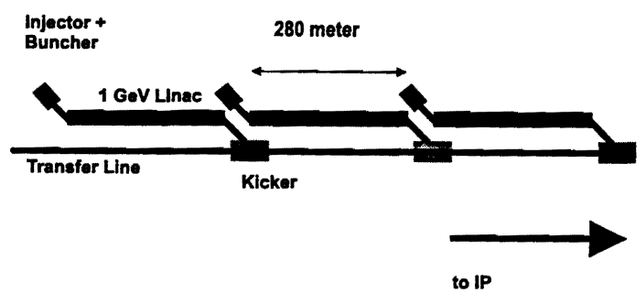

Figure 3 The sketch shows three 1 GeV linacs with an injector and an extraction into the beam line each. The beam line runs parallel to the main linac to transport the bunch train to the compressor ring area close to the interaction point similar to the CLIC scheme.

IX. The Economics of the Upgrade

The investment costs as well as operation costs for a newly constructed 937 MHz linac have to be compared with the rearranged S-Band Linear collider components to decide whether this solution should be considered any further. Because the transfer structures and the main linac would have to be build in any case it will not be taken into account. On the other hand construction costs and full operation costs are not well known for either of the two proposals. Therefore only the main arguments which would have to be considered will be listed here.

Pros

- The cost driving items in a normal conducting accelerator are always the klystrons and the modulators. They would not be changed. Also the waveguide and drive-power system would stay in the tunnel.
- The structure, as being proposed here, is much cheaper to fabricate than a standard high gradient structure. Due to the short beam pulse length and the high group velocity it is very well suited for high current operation. Tolerances are very loose as compared to standard structures and power dissipation is small.

• The existing infrastructure for building klystrons in large series could go on with production without any modification

Cons

• 30 kilometer of structure would have to be build instead of 0.5 km, although much more complicated.

• An additional tunnel of 0.5 km length will be required.

• 33 injectors are required instead of one.

• An additional beam line is required if the one for delivering the beam can not be used for transport to the IP as well.

• 2500 Klystrons would have to be operated instead of 200.

X.Summary

The paper summarises the idea of transforming an S-Band Linear Collider, which would have to exist at some time in the future, into a driver linac for two beam operation. A concept and first ideas on how to construct and operate such a linac as well as the technical consequences are presented.

Finally, only a more economical set-up and operation would justify such a decision as compared to the concept being presented by the CLIC team. Unfortunately, because actual data on large sale operation of such an S-Band linear collider does not exist, this is ver difficult to determine today. Therefore only most of the arguments which would have to be considered for such a decision are listed in the final section.

XI.Acknowledgement

The author is indebted to R. Brinkmann and G.A. Voss (both DESY), J.P. Delahaye (CERN) and R. Ruth (SLAC) for contributions, useful hints and helpful discussions.

XII. References

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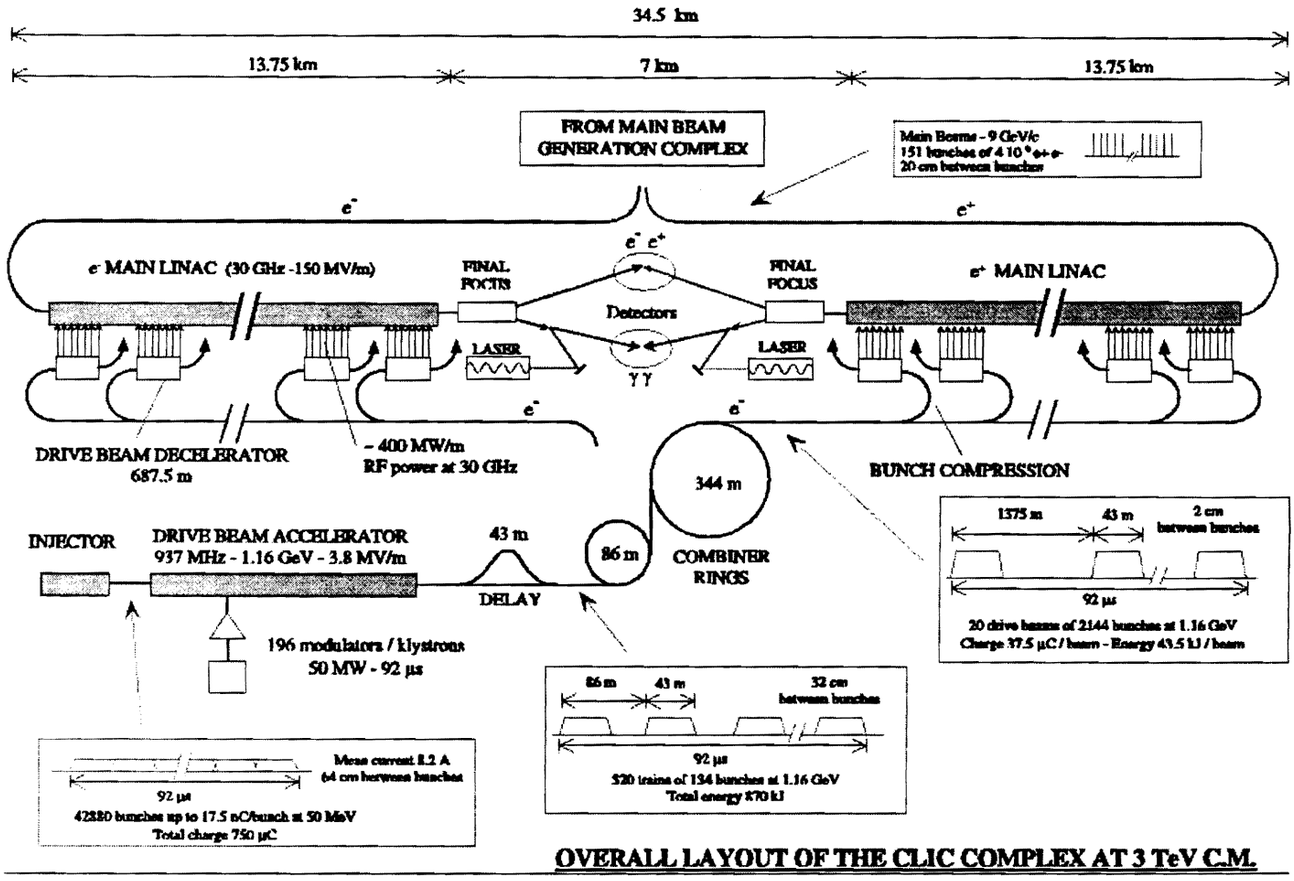

Figure 4:(with courtesy from the CLIC group) In the two beam accelerator scheme of CLIC, the drive beam is generated with a 937 MHz Linac, producing a 1.16 GeV, 8.8 Ampere pulsed current with a pulse length of >90 μsec. Afterwards the continuous beam is compressed into short bursts with a length of 121 nsec, boosting the peak current to 280 amps per burst, which are then distributed in counter-flow direction along the main linac. Due to this distribution system, the total beam pulse length is given by $t_{db}=2L_{linac}/c$.

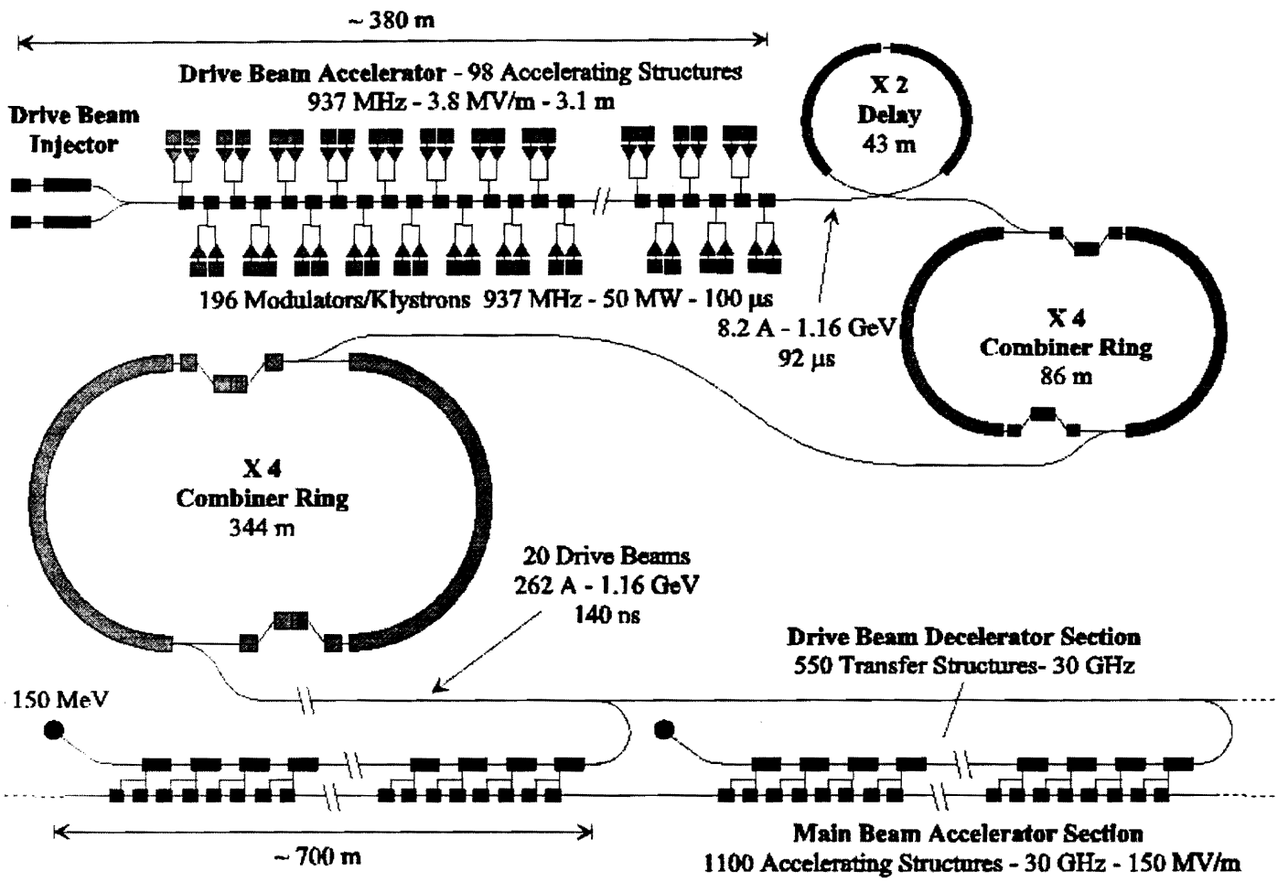

Figure 5: (with courtesy from the CLIC group) The injector complex for CLIC shows the 937 MHz Linac together with the compressor rings which are required nect to the IP. The task of the paper is to compare this linac with a rearranged system ,build from existing components of the S-Band Linear Collider.