EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/PS 92-43 (DI)
CLIC Note No. 176

Two-Beam Linear Colliders

K. Hübner

ABSTRACT

The concept of the Two-Beam Accelerator (TBA) is based on a relativistic low to medium energy but high intensity drive beam generating the rf power for a high frequency (>10 GHz) linear accelerator where a low intensity beam is accelerated to the highest energies. The various methods for converting the drive beam power to rf power and reaccelerating the drive beam are presented. The status of the work in the various laboratories is summarized.

Survey Report presented at
the XVth International Conference on High Energy Accelerators
Hamburg, July 20-24, 1992

Geneva, Switzerland
July 1992

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K. HüBNER

PS Division, CERN, CH-1211 Geneva 23, Switzerland

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The concept of the Two-Beam Accelerator (TBA) is based on a relativistic low to medium energy but high intensity drive beam generating the rf power for a high frequency (>10 GHz) linear accelerator where a low intensity beam is accelerated to the highest energies. The various methods for converting the drive beam power to rf power and reaccelerating the drive beam are presented. The status of the work in the various laboratories is summarized.

1 INTRODUCTION

Linear electron-positron colliders will require accelerating gradients of 0.1 GV/m or more to obtain energies in the TeV range with a reasonable length of the accelerator. Amongst all approaches the one based on a normal conducting rf linac with a resonant frequency f one order of magnitude above the present linacs (1 to 3 GHz) seems to be a viable proposal. The choice of a very high frequency is attractive as the required total peak rf power $\sim f^{-1/2}$ and the average power f^{-2} for a fixed gradient. The high gradient implies high rf peak power per unit length (0.2 to 1 GW/m) even at high frequency. The rf power generators must be capable of delivering this power with a high efficiency in order to keep the power drawn from the grid within reasonable bounds.

At lower frequencies (<20 GHz), the use of klystrons can be contemplated but short, high energy rf pulses seem to be difficult to reach as can be inferred from the very slow evolution of the klystron performance. The current solution is to accept longer pulses from the klystron and to shorten them in an rf compressor in order to match them to the filling time of the accelerating sections. The compressor, however, lowers the efficiency. At higher frequencies (>20 GHz), high power klystrons do not exist mainly for the simple reason that the smaller dimensions preclude a high current electron beam in the klystron. This is the realm of the Two-Beam Accelerator (TBA).

The principle of TBA, proposed in 1982[1], is based on a high intensity, but low to medium energy relativistic electron drive beam running along the whole linac or at least a large fraction of it. It is periodically interacting with either wiggler magnets, rf cavities or travelling wave (TW) rf structures. It excites electro-magnetic fields in these rf devices or amplifies the e-m field in the wiggler via single-pass free-electron laser (FEL) action. Hence, the drive beam is decelerated and beam energy converted into e-m energy; the latter is then coupled out and led by waveguides to the main linac accelerating a beam of lower intensity to the highest energies. Obviously, the drive beam has to be appropriately bunched for effective interaction with decelerating cavities or structures.

In order to keep the energy of the drive beam approximately constant the decelerating sections are interleaved with short accelerating sections. In order to increase efficiency, the energy of the drive beam at the end of the last decelerating section is as low as possible and as still compatible with good transmission. Acceleration and re-acceleration of the drive beam can be accomplished by induction units or superconducting cavities.

Various combinations of these different deceleration and re-acceleration methods have been studied in detail. This paper summarizes the different approaches, their status and their specific problems. The subtitle refers to the method of rf generation and acceleration of the drive beam.

The general layout of linear colliders and the issues common to all approaches, such as damping rings, final focus and general beam dynamics can be found in the Proceedings of the recent European and US Particle Accelerator Conferences.

2 RF GENERATION BY FEL, ACCELERATION BY INDUCTION LINAC

Work at LBL, LLNL and MIT

The first TBA scheme proposed[1] was based on FELs decelerating a drive beam and acting as 30 GHz power sources. The beam is reaccelerated by induction units interleaved with the FELs. The required output power of the FEL was estimated to be 1 GW/m produced by a 3 MeV 1 kA drive beam of 25 ns pulse length. The expected gradient in the main linac was 250 MV/m.

An impressive amount of work on this type of TBA has been done subsequently by a collaboration between LBL, LLNL, MIT and Haimson Research Corporation since this scheme was proposed.

In order to test the principle, an Electron Laser Facility (ELF) was constructed at LLNL. The facility operated at 34.6 GHz and produced more than 1 GW peak output power with 34% efficiency. It consisted of a 3 m long pulsed wiggler with a 9.8 cm period length and 5 kG peak field on axis. The injector was the LLNL Experimental Test Accelerator providing a 0.5 kA beam of 15 ns length at 3.3 MeV[2].

A seven-cell copper test structure powered with a 34.6 GHz, 3.1 MW, 15 ns rf pulse from this FEL reached a gradient of 180 MV/m. Encouraged by this result two sections (34 cells, $2\pi/3$, quasi-constant gradient, disc-loaded, 10 cm long, 33.3

GHz) were designed. One was electroformed and the other machined and brazed. Only the latter could be finished but was never tested at high power at LLNL as ELF was dismantled in 1989[3].

In order to continue this important development, a test stand at MIT is in preparation [4]. The 60 MW FEL of MIT will be able to produce accelerating gradients up to 240 MV/m.

The initial TBA design assumed that the beam in the wiggler would travel in an over-moded waveguide. Experimental work showed that the coupling out of the rf power was very difficult; the specially developed septum couplers broke down at low power level. Other extraction methods were also found to be not satisfactory. In order to dodge these problems, it was suggested [5] to use the beat-coupling[6] as the method for rf extraction.

In this now favoured approach, the drive beam traverses inside the wiggler an over-moded cavity where a standing wave (e.g. TE_{01}) is excited by FEL interaction. The cavity is side-coupled to an accelerating cavity of the main linac. The stored energy is periodically exchanged between the two cavities, the drive beam replenishing via FEL the power delivered to the main beam. Fig. 1 shows a possible layout.

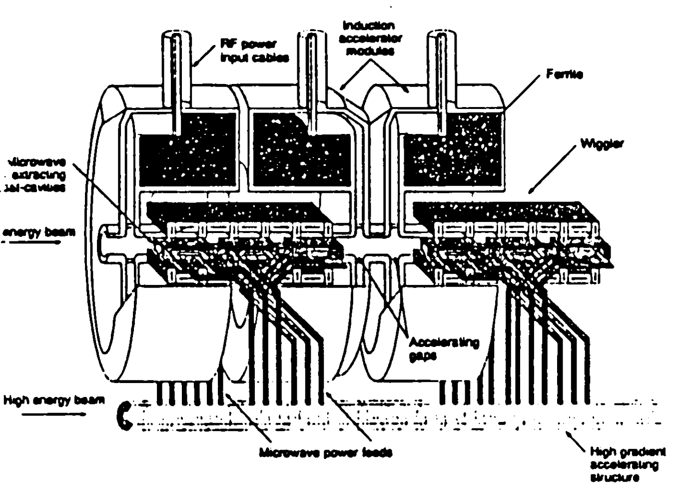

Fig.1 - Possible layout of FEL driven TBA according to LBL/LLNL. Drive beam acceleration by induction cells

A possible set of drive beam parameters is I=2.2 kA peak current, 14 MeV beam energy, 6 ns pulse length and 1% relative energy spread. The wiggler field B_W is 5.4 kG, the wiggler period λ_W=25 cm, the cavity transverse dimension h·w=3 cm·10 cm, the operating frequency 17 GHz and the output energy generated per shot and unit length

$$\frac{dW}{ds} \sim \left(\frac{I \cdot \lambda_W \cdot B_W}{\gamma}\right)^2 / (h \cdot w) = 10 J/m$$

The TBA period is typically of the order of one meter[5].

Various coupling arrangements have been examined theoretically: coupling by a single-mode waveguide, direct coupling by means of holes in the cavity walls or indirect coupling through a third intermediate transfer cavity. Transfer efficiencies between 80 and 90% are computed for the last but one case and 95% for the last case[7].

The advantages of the standing-wave FEL are that the microwave power is lower and does not propagate through the induction accelerator cells, which reduces the danger of breakdown.

Extensive numerical simulations have been done to understand sensitivity to fluctuations in drive beam parameters. For example, in order to limit the phase error to 0.1 rad, the initial relative energy fluctuation in the drive beam must be smaller than 0.1% and the jitter in the reacceleration field must be much lower than 0.1 ns[5]. Other effects studied theoretically are drive beam loading due to the longitudinal wake of the induction cells[8], transverse beam break-up of the drive beam due to its interaction with the induction cells[9] and the resistive walls in beam pipe and wiggler magnet[10,11].

Although progress in the understanding of theory is impressive, the very desirable experimental work for guidance and verification of the approach has not been pursued because of lack of funds.

Work at KEK

This approach, where the drive beam traverses periods consisting of a FEL and induction cells, has also been adopted by a group in KEL/Japan[12]. Fig. 2 shows their conceptual layout of a linear collider with 1 TeV in the centre-of-mass. Six

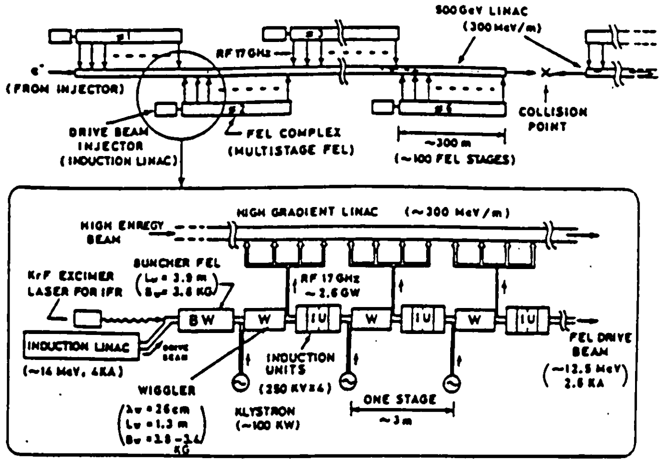

Fig. 2 - Concept of a 500 GeV TBA by KEK

multi-stage FEL complexes provide 17 GHz rf power to the main linac operating with a gradient of 300 MV/m. Each FEL complex consists of an induction linac injector and a set of wigglers interleaved with induction units for drive beam reacceleration. Each wiggler produces 2.6 GW rf peak power. In order to ensure good transmission of the 12.5 MeV, 2.6 kA drive beam, ion focusing is proposed. The drive beam pipe is filled with a relatively heavy gas ionised by a KrF laser prior to beam injection. The intense drive beam ejects electrons from the plasma and is focused by the remaining column of positive ions, which helps to compensate space charge and protects the beam from instabilities.

In order to test these ideas, a test stand has been built at KEK[13] as shown in Fig. 3

The Test Stand consists of an induction linac injector, a wiggler, the microwave system and the laser. The induction linac is formed by 4 cells each providing 200 kV with 80 ns pulse duration. Hence, the electron beam drawn from a 50 mm diameter velvet cathode is accelerated to 800 keV. The induction cells are driven by two magnetic pulse compressors each supplying a peak power of 3.2 GW. After selection of emittance which reduces the beam current to 0.5-0.7 kA, the beam enters a planar wiggler with 15 periods and λ_W=16 cm.

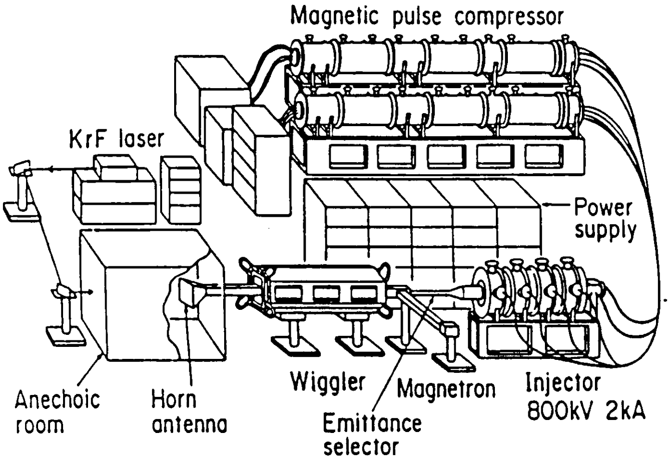

Fig. 3 - KEK Single-Stage X-band FEL Test Stand

The wiggler peak field is 1.9 kG, the field optimizing the power output is 0.62 kG. The wiggler is pulsed at 0.1 Hz. The microwave source is a pulsed 100 kW magnetron providing about 30 kW for 2 µs launching a TE_{01} wave in the 5.5 cm x 11 cm over-moded waveguide. The wave is amplified by the beam and then transmitted to an anechoic chamber for power measurement. The beam channel is filled with Diethylaniline ionised by the KrF laser. A 90% beam transmission can be obtained over the useful range of wiggler field by adjusting the gas pressure which is typically 0.3 m Torr at the wiggler's exit.

The programme started in 1985 and by 1990 1 MW FEL output was achieved. The maximum power attained by now is 30 MW for 30 kW input. The output pulse length is 40 to 50 ns (FWHM) for a 80 ns long beam pulse. The maximum measured gain in the wiggler is 22 dB/m; no saturation was observed in agreement with calculations which reproduce the gain versus wiggler field data quite well and predict saturation at 50 MW output level.

Parallel to the experiment the theoretical effort focused on effects which could perturb good transmission of the drive beam through many FEL units. High transmission is mandatory for good overall efficiency. The main effects scrutinised were the beam break-up instabilities including resistive wall instability. The methods for controlling these instabilities (Landau damping generated by the non-linearity of the ion channel[14], damping by an energy variation along the beam[11]) have been examined. The most recent proposal is stagger tuning of the deflecting TM modes in the induction cells by changing the gap radius linearly along each FEL complex. Preliminary calculations indicate that as many as 200 FEL would be powered by the same drive beam[15].

After successful accomplishment of the first phase of the tests, preparations are being made to increase beam energy to 1.6 MeV by adding eight 200 kV induction units in order to decrease space charge effects which dominate in the test stand according to calculations. Four of these induction units were designed for high vacuum operation so that the velvet cathode can be replaced by a thermo-ionic cathode. An improvement in gain is expected (>30 dB/m). Tapering the wiggler field will raise the output power to several hundreds of MW, enough to conduct the first tests of a 9.4 GHz accelerating structure. As a next stage, a further increase of the drive beam energy to 5 MeV is contemplated, which would be high enough so that the same drive beam could traverse a number of FEL/induction units.

Work at JINR/Dubna

The concept of using a FEL as rf power source is also studied experimentally and theoretically at Dubna. Recent work[16] is based on the experience gained from an earlier test stand where 30 MW output power at 35 GHz was obtained from a tapered wiggler[17]. An induction accelerator is used as injector for the tests stand in preparation (Fig. 4).

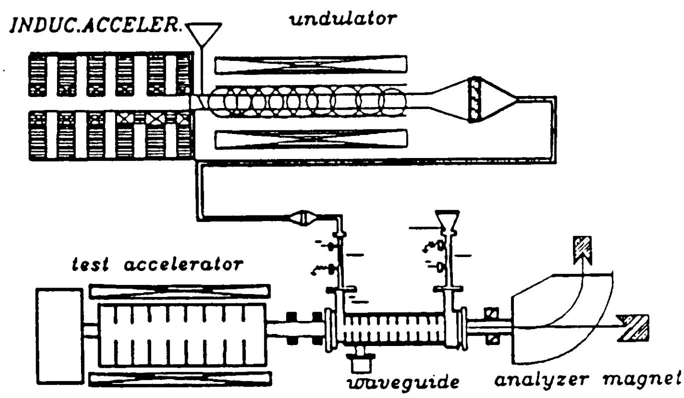

Fig. 4 JINR 35 GHz FEL Test Stand

It delivers a 3 MeV 0.5 kA annular electron beam with 5% energy spread; the pulse length is 70 ns and the repetition rate 1 Hz. The accelerator consists of three 1.8 m long sections providing 0.6 MV/m at 1 kA; each section contains 12 induction modules powered by 4.5 to 7.5 GW pulse modulators. The FEL amplifier is based on a helical undulator (λ_w=10 cm, $B_w$peak=0.4 T) immersed in a 1 T axial solenoidal field. For input matching of the beam the undulator field increases smoothly over the first six periods and the undulator design allows for tapering to increase efficiency. A 50 kW magnetron provides a TE_{01} wave which is fed to the stainless steel circular (r=1.45 cm) waveguide after conversion to a linearly polarised TE_{11} mode. After amplification, the latter is reconverted into a TE_{01} mode and fed to the accelerating structure. An output power of 200 MW is expected with the 2.5 m long tapered wiggler. The programme also includes the study of high gradient TW disk-loaded accelerating structures at 20 and 35 GHz. At 35 GHz the following parameters were chosen: $2\pi/3$ phase shift per cell, iris radius 0.15 cm, 150 MV/m (233 MV/m at surface) with 80 MW input, 60.5 ns filling time. In order to verify the accelerating gradient, a test beam from the LUE-10 accelerator will be accelerated from 5 to about 20 MeV in the high-gradient structure.

The induction accelerator has delivered a 3 MeV 0.35 kA beam and the first FEL experiments with a short (1 m) undulator are under way. The experiments show that it is not easy to achieve a good frequency and phase stability of the radiation. Calculations taking into account the energy spread of the beam and space charge have shown that the cyclotron rotation should be opposite to the undulator helicity and that an energy spread of 3% reduces the output power by 20%. An accelerating structure of 20 cm length is being manufactured with a dimensional accuracy of better than 1.3 µm, which poses a number of technological problems. The maximum achievable accelerating gradient, dark current and beam loading will be examined in the first tests.

3 RF GENERATION BY RF TRANSFER STRUCTURE, ACCELERATION BY INDUCTION LINAC

Following a suggestion by W.K.H. Panofsky a method for energy extraction from a pulsed beam produced by an induction accelerator was proposed based on bunching of the relativistic beam and on passing it through extraction cavities. Induction units interleaved with the cavities keep the beam energy approximately constant and thus the beam remains usable over a long distance. The appropriate longitudinal beam structure is produced by chopping using transverse deflection and slits after the induction linac[18].

In the first test of this concept, however, a klystron type velocity bunching was tried by a SLAC/LLNL/Haimson R.C./LBL collaboration. The set-up produced a power of 170 MW for 40 ns at 11.4 GHz with a 1.3 MeV 630 A beam as input. The maximum total power achieved was 290 MW. A 26 cm long TW accelerating structure was coupled to this device and, for 80 MW output, a gradient of 84 MV/m was measured with a probing low energy (35 keV) electron beam[19].

After this first test, a research programme[20] has been defined by LLNL going back to the original idea of chopping the input beam. As a first step, a device called choppertron, shown in Fig. 5 has been constructed.

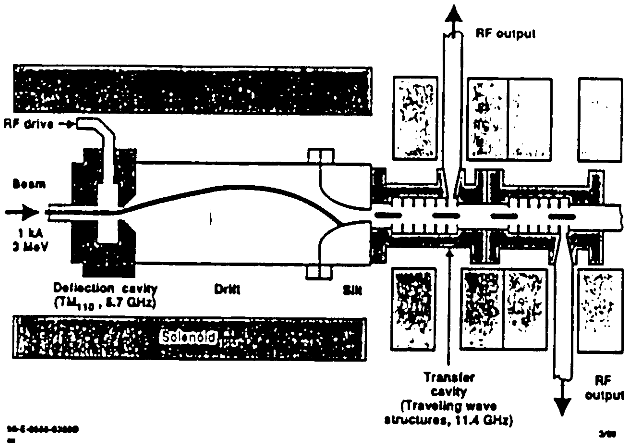

Fig. 5 Schematic layout of choppertron (LLNL)

The deflecting TM_{110} field is generated in a cavity operating at 5.7 GHz and the rf power in two TW structures tuned to 11.4 GHz where a TM_{01} mode is excited by the beam. These 5.25 cm long structures consist of 6 cells and are designed by Haimson R.C. for 250 MW output power and a maximum surface field of 130 MV/m. A third structure was designed with a circuit damping the HEM_{11}-like transverse modes[21]. Using two undamped structures, a maximum total output power of 420 MW was obtained with a 2.5 MeV 1 kA input pulse; the pulse length was 70 ns (FWHM). The pulse shape of the transmitted current and the rf power became distorted above 600 A which is believed to be caused by deflecting fields in the output structures. An output power of 150 MW was easily obtained with a single undamped structure for 1 kA input current but only 120 MW were reached with the single damped structure. Presumably, the damping of HOM also affected the fundamental. Good phase stability across the rf pulse was measured as expected because the transverse modulation is insensitive to beam energy variations.

A reacceleration experiment is planned with a 5 MW 1 kA beam transported through three TW structures with induction cells between them (Fig. 6).

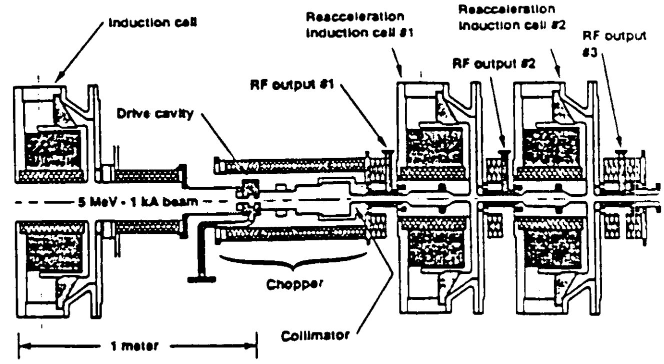

Fig.6 Layout of reacceleration experiment (LLNL)

4 RF GENERATION BY RF TRANSFER STRUCTURES, ACCELERATION BY SUPERCONDUCTING CAVITIES

The CERN Linear Collider study started in 1987 with the emphasis on a facility with 2 TeV in the centre-of-mass. It explores the possibility of using 30 GHz for the main linear accelerator for reasons of power economy. The approach was from the beginning very broad,embracing all key components of the linac, the injection system and the final focus[22].

The rf power is generated by one medium energy (6 GeV) electron drive beam running along the whole linac and traversing rf transfer structures, with a few short sections providing reacceleration. This beam runs parallel to the main beam at about 1 m distance and periodically deposits energy in the 30 GHz TW transfer structures wherefrom a 40 MW, 11 ns rf pulse is fed into each of the four accelerating (80 MV/m) TW structures of the main linac coupled to it. In order to keep the drive beam highly relativistic and preclude excessive transverse blow-up, the drive beam is reaccelerated in 0.35 GHz superconducting cavities. The cavities are lumped together in three strings in order to limit the number of costly access shafts. The initial acceleration of the drive beam is also performed by this type of cavity.

Recently, taking into account the strong interest in a smaller facility, emphasis was put on a 2x250 GeV version. Table 1 lists the most important parameters[23].

Final energy	250 GeV
RF frequency	30 GHz
Bunch population	6×10^{9}
Bunch length	0.17 mm
Repetition rate	1.7 kHz
Total initial normalized emittance	1.5×10^{-6} rad.m
Initial emittance ratio	29
Final normalised emittances x,y	$1.8\times10^{-6}/2.0\times10^{-7}$rad.m
Beam size at crossing point x,y	90/8 nm
Critical photon to particle energy	0.15
Beamstrahlung energy spread	5.9%
Single bunch luminosity	8×10^{32} $cm^{-2}s^{-1}$

Table 1. List of CLIC parameters

Since the linac for 250 GeV is now only 3.3 km long, the initial peak energy of the drive beam is reduced to 3.3 GeV and the drive beam is not reaccelerated at all, which considerably simplifies the scheme.

Each 250 GeV linac will contain about 11000 travelling wave sections of about 35 cm overlall length. Hence, high priority was given to the development of a fully engineered prototype. The iris-loaded accelerating section contains 84 cells and has a coupler to a WR28 waveguide at each end. The aperture diameter is 4 mm and the outer diameter of the structure is 35 mm; the latter serves as reference for alignment, and is therefore machined to ±1 μm precision and concentricity relative to the beam aperture. After the finishing of a 30-cell prototype a first complete structure [24] has been built, tested and installed in the CLIC Test Facility described below. Although brazing was done at CERN, machining of the cells was done in industry, demonstrating the possibility of industrial production. The next step is the study of cell-to-cell stagger tuning to cancel multi-bunch wakefields[25].

To stabilize the beam against transverse single-bunch wakefield effects, it is planned to replace a fraction of the accelerating structure by micro-wave quadrupoles formed by oval-bodied cells with a circular aperture. These cells produce simultaneous acceleration and time-dependent focusing which is stronger for the tail than for the head of the bunch. Precision-machined prototypes of such cells have been produced[26].

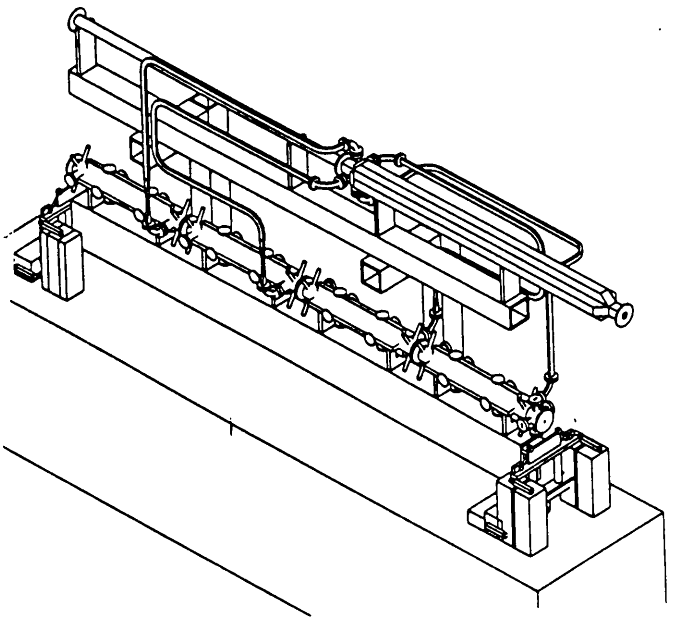

Fig. 7 A 1.4 m long module of CLIC. The drive beam and a transfer structure on top feeding four accelerating sections below.

Fig. 7 shows a module of CLIC. After pre-alignment[27] of the accelerating sections and the quadrupoles, which are on independent supports, an algorithm based on the measurements by the beam position monitors (BPM) with a micron accuracy will yield the displacement of the quadrupoles required for trajectory correction. This will also approach the quadrupoles to the ideal line. The quadrupoles are positioned by high-precision micro-movers. The BPMs, placed as close as possible to the quadrupoles, form the front-part of the first accelerating section on the girder. The BPM consists of a E_{110} cylindrical cavity with an eigenfrequency of 33 GHz, 3 GHz above the fundamental, which minimises interference. Common mode rejection (30 db) is achieved through a magic tee fed by 2 diametrically opposed outputs. Such a cavity has been machined and the effect of the passage of an electron bunch was simulated using an antenna placed just outside the cavity. The reduction of precision due to common modes is estimated to be 0.1 μm. The dependence of voltage on position is very linear. These results show that this system is capable of measuring positions accurately to below one micron[28]. A pair of BPMs with their rather sophisticated electronics[29] will soon be tested with an electron beam in the CLIC Test Facility.

In order to test alignment concepts and key components, a micro-movement test facility has been built in an unused underground tunnel. It uses two girders and three platforms and is equipped with high-resolution transducers (0.1 μm and 10 μrad resolution). The girders articulate about a common movable point which is supported by a platform. The latter is activated by three precision jacks for orthogonal transverse displacement and axial rotation. After a deliberate perturbation (e.g. 1 mm), the system settles back to nominal position within less than one micron[27]. A new 6 girder test facility equipped with a newly developed optical pre-alignment system (precision 1 to 2 μm over 6 m) is under construction..

In order to establish the required precision of alignment, extensive simulations have been performed[23].

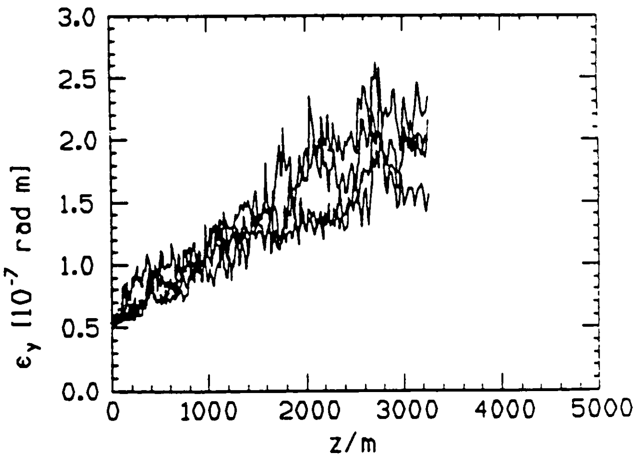

Fig. 8 Evolution of vertical emittance in 250 GeV CLIC linac

Fig. 8 shows a simulation of the evolution of the vertical emittance with 4 different seeds of alignment errors of quadrupoles (1 μm rms) and accelerating sections (5 μm rms) assuming a simple one-to-one trajectory correction centering the beam in each BPM. The latter is assumed to have the same alignment error as the nearby quadrupole. It can be inferred from the simulation that the required final emittance of 2x10-7 rad.m (cf Table 1) can be achieved. If, contrary to the previous assumption, the BPMs are not attached to the quadrupoles but have an independent alignment error of 1 μm, the quadrupole alignment tolerance can be relaxed to 3 μm. More refined achromatic correction schemes are expected to relax the tolerances further[30,31].

The rf power is generated in the transfer structures by the drive beam. The drive beam pulse is arranged in four trains spaced by 2.84 ns=λ(351 MHz)/c which is also the drain time of these structures. Thus after the passage of the four trains a 4x2.84=11.4 ns long rf pulse is produced by each transfer structure. This pulse length equals the filling time of the accelerating structures. Each train consists of 43 bunches spaced by λ(30 GHz)=1 cm. The bunch length should be $\sigma_z \leq$ 1 mm to ensure efficient energy transfer. The total charge per drive pulse is 7 μC.

The transfer structure consists of a smooth round beam chamber with four longitudinal coupling slits connecting to rectangular waveguides running parallel to the beam on the outside (cf. Fig. 7). The TEM wave accompanying the bunches causes constructive excitation of the TM_{11} forward mode in the waveguides. The waveguides are loaded with ribs in order to match the phase velocity of the TM_{11} wave to c at 30 GHz. The about 1 m long structure provides 53 MW in each output wave guide[32]. The rf transfer efficiency to the main linac is assumed to be 70% until measurements become available.

In principle, each drive train could consist of only one bunch but, for reasons of beam stability, the charge must be distributed over many bunches, which also eases the production of the beam. Hence, 43 bunches have been chosen which makes one train 42 cm long. The energy of the bunches has to vary linearly within the train to match the roughly linear build-up of the decelerating voltage in the transfer structures. The required energy distribution in this bunch train having a length of about λ(0.35 GHz)/2 is produced in the drive linac by adding to the fundamental (h=1, 0.35 GHz) higher harmonic cavities at h=2 and 4 driven by the beam. In order to compensate the beam loading, the 0.35 GHz cavity complement is split into two groups; each group operates at a frequency deviating slightly from the fundamental. These methods are used for initial acceleration as well as for reacceleration.[33].

In order to find the required drive beam injection energy, extensive simulations have been performed[23,34]. The bunches in the drive beam have a very large energy spread at the end of the linac. This is caused by the strong deceleration of the core of the bunches in the transfer structure, desirable for reasons of efficiency and the fact that the tails are hardly decelerated,being far from the crest of the decelerating 30 GHz voltage. The simulations including wakefields, focusing, alignment imperfections and trajectory corrections lead to the conclusion that a drive beam with an initial peak energy of 3.3 GeV can be transmitted,though the lowest energy at the end is only 0.86 GeV. Fig. 9 shows the initial and final energy distribution in the drive beam.

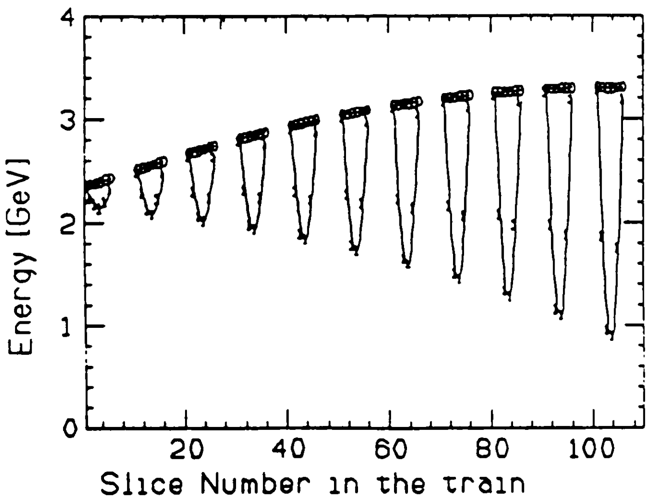

Fig. 9 Initial (o) and final energy distribution (x) in CLIC drive beam (old version with 11 bunches shown).

Drive beam and main beam simulations were also performed assuming 24 GHz as operating frequency, in order to provide a factual answer to the legitimate question how much could be gained if a frequency lower than 30 GHz were chosen[23]. The longitudinal wakes would be reduced to 64% and the transverse wakes to 50%. Keeping at the same time the total average rf power constant leads to a reduction of the accelerating gradient to 51 MV/m and, in turn, to a longer linac. Analysis of the results leads to the conclusion that the gain in beam stability and emittance blow-up is marginal as the reduction in the wakefields is offset by the lengthening of the linac.

The generation of the high-intensity drive beam with its particular configuration and bunch length of 1 mm has received much attention[22]. The most promising solution seems to be to produce a high-intensity electron beam pulse from an induction linac and to have it bunched by a 30 GHz FEL[35]. A FEL scheme based on an rf linac was worked out for the originally shorter (11 bunches) drive trains[36]. The longer drive trains, however, are better produced by a 10 MeV induction linac delivering 1 kA. A chopper at some intermediate energy produces the 42 cm long beam pulses which become bunch trains after bunching at 30 GHz in a 5 to 10 m long wiggler. The beam is subsequently accelerated by the superconducting drive linac[37].

In order to study an alternative for the drive beam generation and to have a facility producing short bunches, the CLIC Test Facility (CTF) has been built[38]. It consists of a BNL-type 3 GHz rf gun operating with 70 MV/m and having a laser-driven CsI photocathode. The beam is accelerated in a 4.5 m long 3 GHz TW linac structure with a non-load voltage of 48 MV. The objective of a first test series was to study the gun behaviour and produce some 30 GHz power by having the bunch train traverse one passive CLIC 30 GHz accelerating structure. With an 8 ns long laser pulse at 213 nm producing a 40 nC bunch train, 80 kW output power at 30 GHz was generated. At present, the rf synchronizable laser providing pulses as short as 10 ps is being commissioned and the first electron bunches were observed. After a second series of tests it is planned to move the rf gun closer to the accelerating section in order to preclude deterioration of the beam by wakefields and space charge. The beam line will be extended to allow for passing the beam also through a second CLIC structure powered by the first one as a probe beam to measure the energy gain in the second structure. Using a bunch train should enable the first structure to produce enough power that a gradient close to the nominal 80 MV/m is reached in the second section. Further subjects for study are: dark current and rf output pulse characteristics of the CLIC accelerating structure; tests of the transfer structure and the BPM are also foreseen. In order to increase the injected current a 5 1/2 cell gun is being designed and an increase of the rf power for the S-band accelerating section is contemplated in order to decrease beam loading which is very severe. In parallel, the development of various types of photocathodes is pursued[39].

ACKNOWLEDGEMENTS

I would like to thank R. Bonifacio, S. Hiramatsu, V.P. Sarantsev, A.M. Sessler and G.A. Westenskow, who helped me patiently to gather information. I had many clarifying discussions with G. Guignard, C. Johnson, J.H.B. Madsen, W. Schnell, L. Thorndahl and I. Wilson, who also read the manuscript as did D. Möhl. Thanks are due to all.

REFERENCES

[1] A.M. Sessler, "The FEL as a power source for a high gradient accelerating structure", AIP Conf.Proc. 91 (ed. P.J. Channel) (1982) 154.

[2] T.J. Orzechowsky, B.R. Anderson, W.M. Fawley, D. Prosnitz, E.T. Scharlemann, S.M. Yarema, Microwave radiation from a high-gain FEL amplifier", Phys.Rev.Lett. 54 (1985) 889.

T.J. Orzechowsky, B.R. Anderson, J.C. Clark, W.M. Fawley, A.C. Paul, D. Prosnitz, E.T. Scharlemann, S.M. Yarema, "High-efficiency extraction of microwave radiation from a tapered wiggler FEL", Phys.Rev.Lett.57 (1986) 2172.

[3] D.B. Hopkins, A.M. Sessler, J.C. Farmer, W.K. Kelley, C.P. Steffani, H.A. Johnson, J. Haimson, B. Mecklenburg, "Design and fabrication of 33 GHz high-gradient accelerator sections", Proc. Europ. Part.Acc. Conf. (EPAC), Rome (1988) 1157.

[4] G. Bekefi. Private communication (1991).

[5] A.M. Sessler, D.H. Whittum, J.S. Wurtele, W.M. Sharp, M.A. Makowski, "Standing-ware free-electron laser TBA", Rep. LBL 30418 (1991).

[6] H. Henke, "An energy recuperation scheme for a two-beam accelerator", CERN Div.Rep. LEP-RF/88-55 (1988).

[7] M.A. Makowski, "RF transfer in the coupled-cavity FEL TBA", Proc. IEEE Part.Acc.Conf. (PAC) (1991) 2548.

[8] D.H. Whittum, A.M. Sessler, G. Graig, J. DeFord, D.U.Yu, AIP Conf.Proc.193 (1989) 433.

[9] D.H. Whittum, G.A. Tavish, A.M. Sessler, G. Graig, J. DeFord, "Beam break-up in the TBA", PAC (1989) 1190.

[10] K. Takayama, "Crucial aspect of beam break-up in a steady state FEL in the microwave regime", Phys.Rev. A39(1988) 184.

[11] D.H. Whittum, A. M. Sessler, V.K. Neil, "Transverse resistive wall instability in the TBA", Phys.Rev.A 43 (1991) 294.

[12] D.H. Whittum, K. Ebihara, S. Hiramatsu, Y. Kimura, J. Kishiro, T. Monaka, T. Ozaki, K. Takayama, "X-band ion-focused FEL", Proc.of this Conference.

[13] S. Hiramatsu, K. Ebihara, Y. Kimura, J. Kishiro, M. Kumada, H. Kurino, Y. Mizumachi, T. Ozaki, K. Takayama, "Proposal for an X-band single-stage FEL", NIM A 285 (1989) 83.

[14] K. Takayama, S. Hiramatsu, "Ion-channel guiding in a steady-state FEL", Phys.Rev. A 37(1988) 173.

[15] K. Takayama, "Beam break-up suppression in a multistage klystron-like FEL: Linear detuning", Note KEK-FEL (Sept. 91); submitted to Phys.Rev. A.

[16] A.A. Kaminsky, A.K. Kaminsky, V.V. Kosukhin, V.P. Sarantsev, S.N. Sedykh, A.P. Sergeev, A.I. Sidorov, G.I. Sidorov, M.V. Yurkov, "FEL as a RF source for linear colliders", Proc.of this Conference.

[17] A.A. Kaminsky, A.K. Kaminsky, S.B. Rubin, V.P. Sarantsev, A.P. Sergeev, "Experiments on the efficiency increase of FEL amplifier on the base of LIU 3000". Part.Acc. 33 (1990) 1879.

[18] A.M. Sessler, S.S. Yu, "Relativistic klystron two-beam accelerator", Phy.Rev.Letters 58 (1987) 2439.

[19] M.A. Allen et al., "High-gradient electron accelerator powered by a relativistic klystron", Phys.Rev.Letters 63 (1989) 2472.

[20] T.L. Houck, D. Rogers, R.D. Ryne, G.A. Westenskow, "Relativistic klystron research for two-beam accelerators", UCRL-JC-108013. To be published Proc. SPIE Symposium on Intense Microwave and Particle Beams II, Los Angeles (1992).

[21] J. Haimson, B. Mecklenburg, "Suppression of beam induced pulse shortening modes in high power rf generator TW output structures", SPIE Proc. Vol.1629-71 (1992).

[22] W. Schnell, "The CERN study of a linear collider in the TeV range", CERN Div. Rep. SL/91-49, presented at the Linear Collider Workshop, Saariselkä (1991).

[23] G. Guignard, "Beam stability simulations in the two CLIC linacs", Proc.of this Conference.

[24] I. Wilson. W. Wuensch, C. Archard, "The fabrication of a prototype 30 GHz accelerating section for CERN linear collider studies", EPAC, Nice (1990) 943.

[25] K.A. Thomson, J.W. Wang, "Simulation of accelerating structures with large stagger tuning", PAC, San Francisco (1991) 431.

[26] W. Schnell, I. Wilson, "Microwave quadrupole structures for CLIC", EPAC, Nice (1990) 3237.

[27] W. Coosemans, I. Wilson, P. Poirier, "An active alignment test facility for the CERN linear collider", PAC, San Francisco (1991) 2070.

[28] W. Schnell, J.P.H. Sladen, I. Wilson, W. Wuensch, "CLIC beam psition monitor developments", Proc.of this Conference.

[29] J.P.H. Sladen, "Signal processing for the CLIC beam position monitor", EPAC, Nice (1990) 735.

[30] T.O. Raubenheimer, R. Ruth," A new trajectory correction technique for linacs", EPAC, Nice (1990) 1405.

[31] C. Fischer, G. Guignard, "Treatment of non-linearities in achromatic trajectory corrections for future linacs", EPAC, Berlin (1992) 729.

[32] G. Carron, L. Thorndahl, "Impedance and loss factor measurements on a CLIC transfer structure", ibid. p 913.

[33] L. Thorndhal, "Multifrequency reacceleration systems for the CLIC drive linac with beam loading compensation", Proc.of this Conference.

[34] G. Guignard, "Tracking code for bunchlet-trains in a drive linac", Proc.of this Conference.

[35] H.D. Shay, R.A. Jong, R.D. Ryne, E.T. Scharlemann, S.S. Yu, "Use of a FEL as buncher for a TBA scheme", Proc. Int. FEL Conf., Paris (1990).

[36] W.A. Barletta, R. Bonifacio, "SNOELF, a FEL-based drive beam injector for CLIC", Proc.of this Conference.

[37] C. Johnsen, Contribution to the ICFA Linear Collider Workshop, Garmisch (1992).

[38] Y. Baconnier, R. Bossart, K.K. Geissler, J.C.Godot, K. Hübner, H. Kugler, J.B.H. Madsen, A.J. Riche, J. Ströde, G. Suberlucq, "The CERN Linear Collider Test Facility", Proc. 15th Linac Conf., Albuquerque (1990) 733.

Y. Baconnier, S. Battisti, R. Bossart, J.P. Delahaye, K.K. Geissler, J.C. Godot, K. Hübner, J.B.H. Madsen, J.P. Potier, A.J. Riche, J. Sladen, G. Suberlucq, I. Wilson, W. Wuensch. "The CERN linear collider test facility", to be presented at the 16th Int. Linear Conf., Chalk River (1992).

[39] G. Suberlucq, "Photocathodes en iodure de césium utilisées à fort courant", Rep. CERN PS-92-29 (LP) (1992).