FEM DRIVE BEAM INJECTOR FOR CLIC

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Abstract

The CERN linear collider (CLIC) study team is now very actively engaged in evaluating various solutions to the technical problem of providing the intense trains of electron bunchlets at 30 GHz that are needed for the RF power source - the Drive Beam. The options range from the use of a conventional electron source at relatively low frequency followed by bunch compression and compaction into 30 GHz trains, to the attractive but more speculative solution of using a Free Electron Maser (FEM) amplifier to induce the 30 GHz time structure directly into the high-current beam from an induction linac. The latter technique was originally proposed by workers at the Lawrence Livermore Laboratory and it is now being studied in collaboration with a number of other laboratories. Some preliminary experimental work has been contracted to CESTA, Le Barp, France. These experiments concentrate on understanding the aspects of the FEM theory that relate to dynamics of the electron beam rather than the more commonly studied behaviour of the accompanying electromagnetic radiation, in particular the dependence of the bunching on beam stability, emittance and space charge. The short-term aim is to provide a low-energy drive beam that could be used for a CLIC test section.

Introduction

The CLIC project group studies the possibility of building an $e^+ e^-$ linear collider with a centre-of-mass energy ranging from 500 GeV to 2 TeV [1].

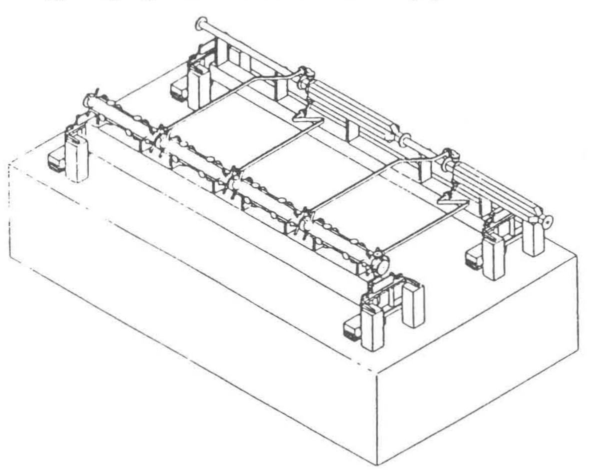

Fig. 1 A 1.4 m long module of CLIC. To the right are shown two transfer structures feeding the four accelerating structures to the left. The 30 GHz power is generated by the drive beam traversing the transfer structures.

The design is based on a two-beam acceleration scheme, in which a high-current relativistic (a few GeV) drive electron beam provides the 30 GHz radiofrequency power to the main high-energy beam. The drive beam runs parallel to the main linac, periodically interacting with properly designed transfer structures, resonant at 30 GHz, by which the generated RF power is delivered to the main beam. In Fig. 1 a 1.4 m long section of CLIC is shown.

The drive beam is composed of bursts at the same 1.7 kHz repetition rate as the main beam, and each burst is composed of one or more trains of short (σ = 1 mm) bunchlets. The bunchlets are spaced by 1 cm, corresponding to the 30 GHz frequency of the transfer structures. The total charge per burst is 7 µC, and the resulting RF pulse must last 12 ns (the filling time of the main linac accelerating cavities), which therefore corresponds to the minimum burst length. By using RF pulse compression between the transfer structures and the accelerating structures, electron bursts with a length up to ~ 50 ns can be used [2].

In this way the average current in the burst and the charge per bunchlet can be made smaller without affecting the RF power and the accelerating gradient seen by the main beam. A low charge per bunchlet is desirable in order to minimize space charge induced debunching and energy spread. In any case, the bunchlet charge is limited to less than 40 nC by the radial electric field strength within the transfer structure (maximum allowable 200 MV/m).

The acceleration of the drive beam up to the final energy will be made using 350 MHz superconducting cavities of the type developed for LEP. Several options are considered at present in order to generate the time structure of the drive beam [3], namely:

- acceleration of individual bunchlets in the SC linac and recombination at high energy by longitudinal stacking in a ring.
- generation of the time structure at moderate energy (~ 40 MeV) and subsequent acceleration to final energy in the superconducting linac.

In this paper we will concentrate on the latter option, and in particular on the use of an induction linac as an electron beam source, followed by a free electron maser (FEM) amplifier to induce the needed 30 GHz bunching in the beam. The post-acceleration to 3 GeV in the 350 MHz SC structures is made possible by dividing the long (≤ 80 ns) pulse from the Induction Linac + FEM into bursts of 4 or more trains by using a chopper. The trains are separated by 2.8 ns (1/350 MHz) and typically have a length of 720 ps. Harmonic acceleration is used to flatten the energy distribution along the train [4].

In Fig. 2 the proposed time structure of the drive beam is shown, in the case of FEM bunching.

- 8 trains of 22 bunchlets
- bunchlet length 1 mm , spacing 1 cm
- bunchlet charge 40 nC

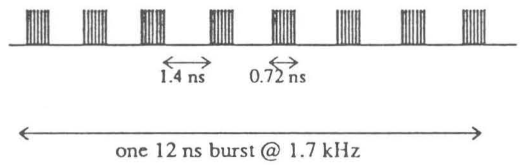

Fig. 2 Drive beam time structure

In this case two bursts are combined after acceleration to obtain a spacing of 1.4 ns between trains (more explanations will be given later).

FEM Induced Bunching

In a Free Electron Maser high-gain amplifier, an electron beam is injected together with a microwave pulse in the spatially periodic magnetic field of a wiggler. The wiggler magnetic field induces a transverse component in the electron velocity, thus allowing the coupling with the transverse electric field of the microwave pulse. If a resonance condition between radiation phase velocity and longitudinal electron velocity is satisfied, the interaction leads to an exponential amplification of the microwave power and to a corresponding bunching of the electron beam, until the onset of a saturation mechanism [5,6]. Such a device is normally used as a radiation amplifier. Its use as a buncher for the drive beam generation has been initially proposed by Yu [7] in 1989 and then further developed [8,9]. The bunching mechanism in the FEM can be intuitively explained as follows:

- If the resonance condition is satisfied, each electron undergoes a net acceleration or deceleration depending on its phase with respect to the electromagnetic wave. The electrons emit or absorb energy from the radiation pulse according to this phase.
- The electron trajectories in the wiggler field depend on their energy, hence the energy modulation of the electrons is transformed in bunching around a phase that corresponds to emission.
- The electron bunches radiate coherently since they are separated by a radiation wavelength, the radiation power starts to grow.
- The power increase in the electromagnetic wave leads to more bunching, and the process is self-sustaining until the electrons' energy loss is such that the resonance condition is no more satisfied (saturation).

In Figs. 3 and 4 the results of a numerical simulation of the FEM are presented which describe the radiation amplification and bunching process (both figures are taken from ref. 9). The Fourier component at 30 GHz of the electron current is in this case equal to that of a Gaussian bunch of 1 mm rms length, in spite of the residual continuous component of the current apparent from the figure. In principle this component can be eliminated at least in part in the chopper, reducing the total charge needed in the drive beam and increasing the efficiency of the system.

FEM experiments have been successfully performed at frequencies close to 30 GHz [10,11]; the experimental results agreed quite well with analytical and numerical predictions, but the measurements were concentrated mainly on radiation. A clear and direct measurement of the electron bunching is still lacking.

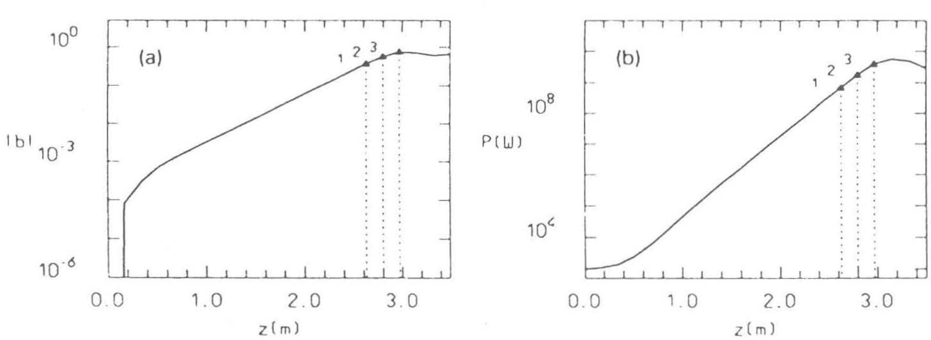

Fig.3 Simulation of the FEL process. We show: (a) the bunching parameter |b|, proportional to the 30 GHz Fourier component of the beam current and (b) the output microwave power in Watts, in a logarithmic scale, as a function of the length of the wiggler, Z (m). For an explanation of the marked points refer to Fig. 4.

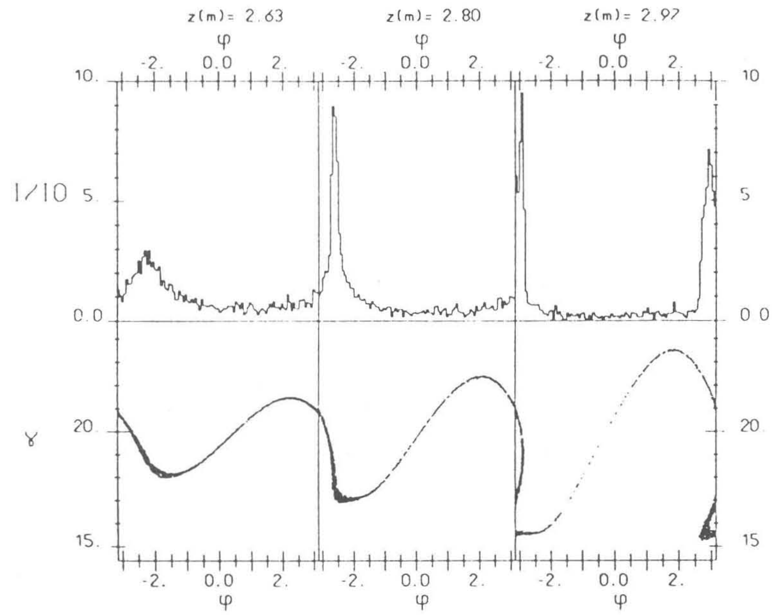

Fig. 4 Phase histogram, showing the electron current in a wavelength (top) and electron distribution in the longitudinal phase space (bottom), at three different locations. Io is the average input electron current. Note the strong peak current (bunching) that can be obtained if one stops the interaction at the proper point (Z = 2.84 m). The three pictures corresponds at the points marked in Fig. 3.

A Possible Layout Using FEM

In Fig. 5 a suggested layout for drive beam generation using a FEM and subsequent acceleration is shown [3].

An induction linac working at 1.7 kHz repetition rate accelerates 80 ns long pulses up to 40 MeV energy.

The pulses are injected into a wiggler together with a 30 GHz RF pulse, and are bunched at this frequency. The pulse is then chopped to obtain 2 times 2 bursts of 4 trains of 22 bunchlets each as indicated in Fig. 5.

The trains are post-accelerated to 3 GeV in two SC linacs composed of 350 MHz LEP type cavities, working in anti-phase. Two linacs are needed due to the strong beam loading in the cavities. In addition, two further sets of cavities per linac, working at slightly different frequencies and properly phased are needed to equalize the energy of the different trains, compensating the beam loading effect [4]. A final set of 4th harmonic (1.4 GHz) cavities is foreseen in order to equalize the energy inside each of the trains. There are no beam loading problems in such cavities, since the train phase extension corresponds to 360° of 1.4 GHz. Four trains from each linac are then combined into a 12 ns burst of 8 trains of 22 bunchlets. The two drive beams are then transported to the two ends of the main linac, where a second harmonic (700 MHz) linac will give at each train the 40% increasing momentum distribution (from the first to the last bunchlet) needed for optimum beam transport in the drive beam line[13]. Such cavities work at zero phase; the momentum is thus transferred from the head to the tail of each train. The main drawback of such a scheme, common to all schemes in which the drive beam time structure is created at low energy, is apparent: the need of beam loading compensation and the use of harmonic acceleration in order to use a sufficient train length oblige us to install ~ 2 × 5 GV of accelerating structures to obtain a mean drive beam energy of 3 GeV. Other schemes are possible, in which a low-energy pulse from an induction linac is chopped and subsequently pre-accelerated to intermediate energy in 350 MHz cavities before being bunched in the FEM.

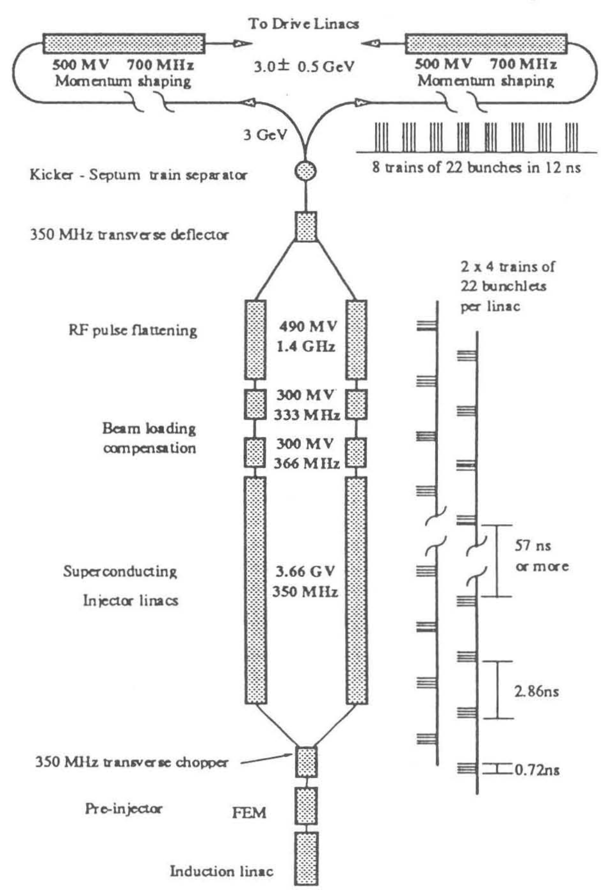

Fig. 5 Possible layout for FEM drive beam generation

The advantage is in capital cost and efficiency, but the strong beam loading in the RF cavities makes problematic to obtain the energy stability along the trains that is needed for phase stability.

Induction Linac and FEM Parameters

The electron source in the above scheme must be able to provide electron pulses of ~ 80 ns, with a current of ~ 1.2 kA, and a repetition rate of 1.7 kHz. The rms normalized emittance required for transport of the beam in the drive linac is 5 10^{-4} m rad. These requirements are within the limits of present induction linac technology.

The choice of FEM energy is fundamental. The cost of the induction linac modules, the possibility of beam breakup in such structures and efficiency considerations force us to keep the beam energy as low as possible. On the other hand, debunching effects are minimum at high energy, so a compromise must be found there. In Fig. 6 the bunch lengthening due to longitudinal space charge forces during acceleration in the 350 MHz linac is plotted for different initial energies, and typical drive beam parameters.

The bunchlet phase must be stable within +/- 10° of 30 GHz; the phase stability depends mainly on the stability of the electron energy along the pulse at injection in the wiggler. Analytical and numerical studies have been made on this issue [13]. The conclusion is that an energy stability of ~ 0.5 % is needed. This is at least a factor two lower than what is typically achieved in existing induction linacs. Further studies are needed on this subject, since some (probably pessimistic) approximations have been used in the simulations and corrections are possible, at least for the linear part of the energy variation along the pulse.

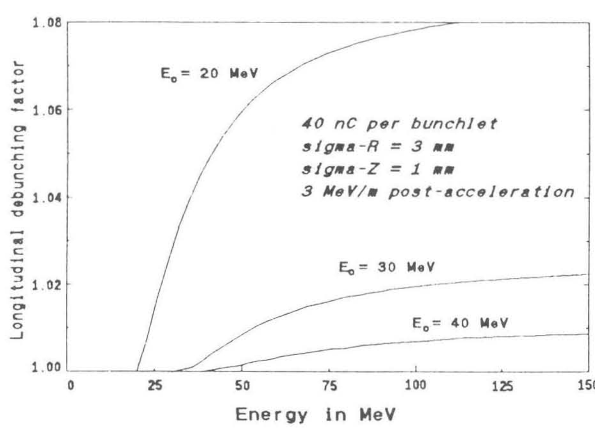

Fig. 6 Bunch lengthening due to space charge during post-acceleration.

Experimental Activities at CESTA

Some preliminary experiments on the FEM bunching process are under way at the Centre d'Etudes Scientifiques et Techniques d' Aquitaine (CESTA) [14]. Both a single-shot pulsed line diode (EUPHROSYNE) and an induction linac (LELIA) are presently used as beam sources. The aim is to perform a direct measurement of the characteristics of the electron beam bunched by FEM action, possibly studying their dependence on beam stability, emittance and current.

A high-gain FEM amplifier experiment has been already operated successfully on EUPHROSYNE, using a 400 A, 1.75 MeV, 20 ns electron pulse. In this experiment a 2 m helical wiggler with solenoidal guiding field has been used. The microwave pulse to be amplified has been provided by a 100 kW, 35 GHz magnetron. The exponential growth of the radiation up to saturation has been observed, in good accord with the simulations (see Fig. 7), obtaining a maximum power of 50 MW in the fundamental TE11 mode (7% efficiency), that should correspond to a good level of bunching. Simulations have shown anyway that, at this energy, space charge and emittance debunching are strong enough to deteriorate the bunching before it is measured. Therefore EUPHROSYNE is being upgraded in energy up to 3 MeV in order to perform a direct measurement of the bunching, using a Cherenkov radiation screen and a high-speed streak camera. This test should be completed before March '94. A higher beam current (up to 1 kA) could also be used in this case (up to now an emittance filter is used to minimize space-charge and emittance effects).

The LELIA induction linac can deliver an electron beam of 1 kA, 60 ns, 2.5 MeV. Such a beam has been already generated and transported last year up to a planar wiggler. Only part of the current (60%) has been injected in the wiggler, due to alignment problems. At present, the induction cells and the guiding solenoids are being re-aligned to optimize transport. Transport of the full current beam through the wiggler is planned before the end of '93.

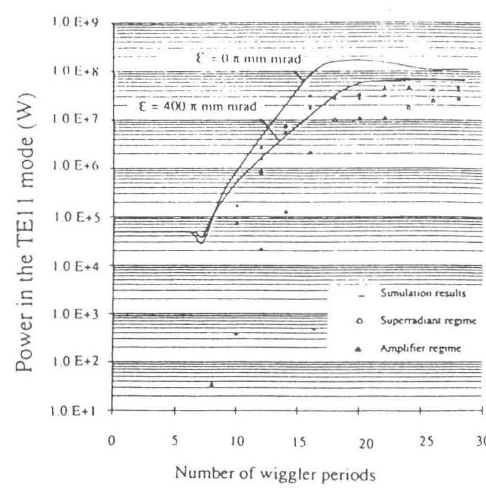

Fig. 7 Measured power (dark triangles) vs. number of wiggler periods in the EUPHROSYNE Free Electron Maser, compared with simulation results. The "superradiant regime" results (white triangles) have been obtained switching off the input signal.

FEM experiments with bunching measurements are planned for the next year on LELIA, using both a planar and a helical wiggler. The characteristics of the electron beam delivered by LELIA are significantly better than the ones of the EUPHROSYNE beam, especially emittance (5.2 10^{-4} m rad - rms normalized) and energy stability (+/- 1% for 25 ns). We expect therefore a more stable operation and a better conservation of bunching after the interaction region. Such a bunched beam can be suitable for use in a two-beam test experiment.

The CLIC Test Section Proposal

A natural extension of the described experimental activity, which is now under discussion, would be the construction of a short section of full-gradient two-beam accelerator. Following the layout presented in Fig. 8, the beam bunched by FEM action, after being extracted from the wiggler will enter one or two transfer structures. The power generated by its interaction is fed into 2 or 4 CLIC accelerating structures, where a probe beam will be accelerated up to ~ 200 MeV. The RF pulse compressor developed at CERN can be also tested in such a scheme, providing the microwave source that provides the input signal to the FEM can switch its phase during the pulse.

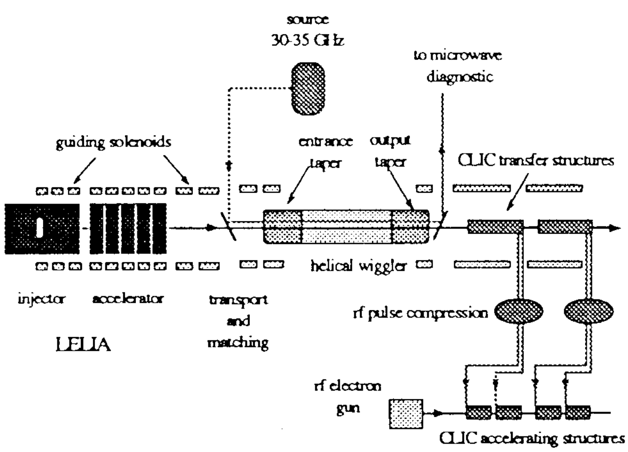

Fig. 6 Layout of the CLIC Test Section Experiment

An adiabatic output taper has already been added to the existing helical wiggler, in order to extract the beam, and alignment tests are being made. The main problem to overcome is the transport of the bunched beam in the transfer structures without losing its temporal structure. Space-charge and emittance debunching are very intense, at this low energy. Numerical simulation studies are presently under way, in order to understand whether or not an energy upgrade of LELIA is necessary and to optimize the transport.

Conclusions

The Free Electron Maser is an interesting candidate for the generation of the CLIC drive beam. Its bunching capabilities are theoretically well understood and indirectly proven by the level of radiation output reached in several experiments. The characteristics needed for the drive beam (current, emittance, pulse length and repetition rate) lead to the choice of an induction linac as an electron source. An improvement in energy stability along the pulse could be needed to reach the desired bunchlet phase stability. An experimental activity is going on at the CESTA Laboratory in Bordeaux, with the aim to study and improve the technology of induction linacs and FEMs. A high-gain FEM amplifier experiment has been succesfully performed, and a direct measurement of the bunching and its phase stability is under way. This activity will hopefully be extended to the use of the bunched beam for RF generation in a short section of CLIC two-beam structure.

Acknowledgments

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