CLIC Drive Beam Generation by Induction Linac and FEL Experimental Studies for the CERN Linear Collider

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Abstract

Generation of the intense 30 GHz drive beam for the CERN Linear Collider project (CLIC) presents several interesting technological challenges. Following recent suggestions to generate this beam using a Linear Induction Accelerator (LIA) and Free Electron Laser (FEL), this option is now actively studied. Newly introduced schemes for harmonic acceleration of the CLIC drive beam, possibly including rf pulse compression, require four or more trains of many bunchlets at 30 GHz and these requirements are well matched to the known performance of the induction linac and FEL. A test facility is being set up at CESTA with the initial aim to generate and measure the properties of a low-energy bunched beam close to the needs of CLIC. An electron beam (1 MeV, 1 kA, 50 ns) created by the LELIA induction injector [1] will be transported through a dipole wiggler in order to generate the low-energy beam bunched by FEL effects. This spatial modulation will be measured by using the Cerenkov radiation analysed by a high-speed streak camera in the picosecond regime. The experimental programme is supplemented by theoretical studies relating to the problems of post-acceleration without significant loss of the essential bunch structure and to the control of phase jitter.

1 INTRODUCTION

CLIC design study explores the technologies that would be required to construct a two-beam linear collider in the center-of-mass energy range from 500 GeV to 2 TeV [2]. The drive beam, that supplies microwave power to a 30 GHz main linac in this two-beam scheme, must be capable of providing trains of intense electron bunches at 30 GHz. Each train, or group of trains within the main linac filling time of 12 ns must contain a total charge of 7 μC and this will be repeated at 1.7 kHz.

Various schemes for generating these bunch trains are under study, mainly involving individually formed bunchlets from thermionic or laser photocathode guns that are compressed to 1 mm bunch length and then combined into groups with 1 cm spacing, i.e. at 30 GHz. The aims are to create bunch structures ranging from four trains of 11 bunchlets each containing 160 nC of charge, the trains being separated by 2.85 ns to permit acceleration over 45 degrees of phase in 350 MHz cavities, to 32 trains of 43 bunchlets of much lower charge, the post-acceleration over 180 degrees of phase being achieved by the use of cavities of second and higher harmonics [3]. In the extreme case

the charge would be spread over three or four filling times with a stage of microwave pulse compression between the drive beam transfer cavity and the main linac accelerating cavity [4]. The trend towards more trains of many bunchlets of relatively low charge favours a solution to the drive beam generation that was initially proposed by Yu in 1989 [5] and then elegantly presented by Shay et al. in 1991 [6].

In the latter proposal a beam of electrons from a LIA is bunched in a single-pass FEL at 30 GHz and the continuous (over 12 or more ns) bunched beam is then chopped into four trains of 11 (or more) bunchlets before post-acceleration in 350 MHz superconducting cavities. This scheme has the extremely attractive feature of requiring just one source of electrons and gives automatic relative phasing of the bunchlets – a non-negligible problem in schemes where the trains are built up from several sources. The chief drawback arises from the need to create the bunchlets at an energy high enough to avoid subsequent debunching from longitudinal space charge forces, since the following acceleration at 350 MHz provides no longitudinal focussing. Also, despite the continuous formation of bunchlets, there will be some bunchlet to bunchlet phase jitter that is mainly related to energy jitter in the electron beam entering the FEL.

The debunching problem can be solved, at the cost of providing sufficient LIA voltage, by increasing the energy at which the beam is first bunched in the FEL. According to the bunchlet charge that we choose, this FEL energy may be from 20 to 200 MeV.

2 POST-ACCELERATION

The mainstay of the CLIC design is the acceleration of the drive beam to GeV energies in 350 MHz superconducting cavities similar to those developed for the CERN electron-positron collider LEP. The cost of acceleration by this means is an order of magnitude less than by the use of LIA. However, because of beam loading and high order mode excitation in the superconducting cavities, to obtain the beam quality needed for correct FEL operation it seems that the LIA is the only candidate for acceleration up to the FEL energy. Hence, there is ample motivation to keep this energy as low as possible. A preliminary study has shown that for a drive beam comprising 4 trains of 22 bunchlets each with 80 nC charge the energy of the FEL should be in the region of 100 MeV. Bunching at a lower energy would result in some loss of 30 GHz structure due to the effect of longitudinal space charge. Reducing the bunchlet charge by increasing the number of bunchlets or

trains of bunchlets (always maintaining the total charge at $7 \mu\text{C}$, or more if the inefficiencies of microwave bunch compression have to be compensated) would allow the FEL energy to be reduced, but then we run into the problem of debunching due to the relatively large transverse emittance of the drive beam.

3 PHASE STABILITY

To obtain the desired conversion efficiency in the CLIC transfer structure, the position of individual bunchlets composing a train should be stable in phase within some degrees. It is therefore essential to know under what experimental conditions this restriction is satisfied.

An analysis has been made to understand the dependence of the position of the bunches on the various experimental FEL parameters. This analysis has been carried out both analytically and numerically. It has shown that the main contribution to the phase difference between the bunchlets comes from initial variations in the electron beam energy along the macropulse, and has substantially confirmed the phase sensitivity evaluations given in [6]. An approximate analytical expression has been derived which gives an upper limit for the variation of the bunchlet phase as a function of energy sweep along the electron pulse:

$$\Delta\Theta \leq 4\pi N_w \left(1 - \frac{X}{2}\right) \frac{\Delta\gamma}{\gamma} \quad (1)$$

where N_w is the number of wiggler periods and $X = k_{\perp}^2/k_w k_{\parallel} = \lambda\lambda_w/b^2$ is the TE01 waveguide parameter; λ_w is the wiggler period, λ the FEL radiation wavelength and b the waveguide height.

The above expression is valid in the FEL linear regime, prior to saturation, and for an energy variation $\Delta\gamma/\gamma \leq \rho$ where ρ is the fundamental FEL parameter (typically of the order of $5 \cdot 10^{-2}$). In steady state condition [7] the waveguide parameter $X = 1$, so the sensitivity is $\leq 0.06 N_w$ (rad / %) $\Delta\gamma/\gamma$. A wiggler tailored to the CLIC drive beam generation will have a number of periods between 10 and 30, depending on electron beam current and energy. The effective phase variation (numerically evaluated) ranges from 0.4 to 1.3 (rad / %) $\Delta\gamma/\gamma$. This will limit the acceptable energy sweep during the electron pulse to values of the order of $5 \cdot 10^{-3}$. A more accurate investigation on acceptable phase jitter in the CLIC transfer structure will set the exact limit.

4 TEST FACILITY

To study the FEL concept for CLIC drive beam generation we shall use the LELIA induction linac at CESTA. This accelerator can deliver a 1 kA, 50 ns electron beam at 1 MeV and will be upgraded to 2.5 MeV before summer '93. A preliminary bunching experiment will use a short hybrid wiggler built to study electron trajectories. As indicated in figure 1 the electron beam is transported from LELIA to the wiggler where it interacts with a copropagating 35

Figure 1: Lay-out of the LELIA facility for the CLIC drive beam experiments

GHz wave delivered by a 120 kW magnetron. The beating of the electromagnetic wave and the wiggler magnetostatic field gives rise to an axial ponderomotive force and a consequent bunching of the electron beam. This process causes the amplification of the injected radiation pulse. The existing wiggler parameters (8 periods of $\lambda_w = 8 \text{ cm}$; $B_w \simeq 1500 \text{ Gauss}$) impose a low energy ($\simeq 1 \text{ MeV}$) operation for 35 GHz amplification. The challenge of this experiment comes from space charge forces, which can cause a loss of beam current during transport between LELIA and the wiggler and, worse, can induce FEL gain degradation and bunching delay. By increasing the electron beam energy such effects can be minimized, permitting higher spatial modulation of the electron beam in the wiggler.

This year is dedicated to electron beam transport along the experimental line at 1.2 MeV and 2.5 MeV, paying particular attention to beam injection and matching into the wiggler. Next year we shall couple the 1.2 MeV resonant electron beam to the 35 GHz microwave radiation delivered by the magnetron; we estimate that at least 50 kW out of the initial 120 kW power generated by the magnetron can be transported and launched in the TE₀₁ mode in the interaction region. Then, once a significant rf power amplification is measured, we shall use the bunching diagnostic to measure the longitudinal electron beam current modulation at the rf frequency.

4.1 The Wiggler

The existing hybrid wiggler is made of permanent magnets alternating with soft iron poles. These are curved in such a way as to assure equal beam focussing in both transverse planes [8]. The wiggler magnetic field inside the structure and near the propagation axis z will approximate the desired field given by:

$$\begin{aligned} B_x &= B_w \sinh k_x x \sinh k_y y \cos k_w z \\ B_y &= B_w \cosh k_x x \cosh k_y y \cos k_w z \\ B_z &= \sqrt{2} B_w \cosh k_x x \sinh k_y y \sin k_w z \end{aligned}$$

where $k_x = k_y = k_w/2$ and $k_w = 2\pi/\lambda_w$.

The magnetic field is measured using a fully automatic Hall probe bench enabling us to obtain the three magnetic

Figure 2: Example of the B_y field measurement on the z axis for a 53 mm wiggler gap showing fringing field to be corrected at the wiggler entrance

Figure 3: 1 MeV, 1 kA, 10 mm diameter, 400π mm mrad beam propagation through the wiggler using the ELECTRA propagation code. $B_w = 1600$ Gauss at $z = 0.1$ m. Some current is lost in this example but a better matching is possible by changing adjustments in the wiggler entrance section $z < 0.1$ m.

field components in the desired locations. An example of the main field component B_y measurement on the z axis is given in figure 2.

4.2 Electron Beam Trajectories

Solenoidal focusing is used inside the accelerator and in the transport line. Initially the required coil current values are evaluated with an envelope code and then adjusted with the help of the PIC code ELECTRA, developed at CESTA, to obtain a 1 kA, 10 mm diameter exit waist.

Figure 3 gives an example of a 1 MeV electron beam beginning its propagation at a 10 mm diameter waist. These results are obtained with the ELECTRA code including transverse space charge. We have built a shuttle with a Cherenkov screen to measure the beam radius at different locations in the wiggler to confirm these calculations.

4.3 FEL computations and bunching previsions

Simulations of the FEL process have been made using the SOLITUDE code [9], developed at the "Commissariat à

l'Énergie Atomique" (CEA) a few years ago, and benchmarked against previous experiments.

This code is a multimode steady-state amplifier FEL code, with a version for rectangular waveguides and planar wigglers, taking into account longitudinal space charge.

Gain reduction and shift in resonant frequency due to longitudinal space charge for various sets of parameters have been studied numerically. The bunching achievable with low-energy operation is quite low and may be difficult to observe.

A great improvement is obtained for 2.5 MeV operation with adequate wiggler parameters ($\lambda_w = 10$ cm, $B_w \simeq 3000$ Gauss, total length $\simeq 1.5$ m); in this case a value of the bunching parameter of $\simeq 0.5$, is shown by the computer simulations.

5 CONCLUSIONS

The FEL bunching scheme for the CLIC Drive Beam requires the development of a high energy 30 GHz FEL with good phase stability. This novel use of an FEL to generate bunched electron beams rather than as a source of radiation requires some studies into the electron beam characteristics within a high-gain microwave FEL amplifier. An experimental approach to this work has now begun at CESTA. The initial two-year programme calls for the generation and transport of a 1 kA electron beam from an induction linac into a hybrid wiggler. After a study of the amplification of input rf power in the fundamental waveguide mode, the electron bunch structure will be measured using a Cherenkov radiator and a high-speed camera.

The experiment will be extended to energies beyond the scope of the existing wiggler, and a suitable 2.5 MeV 35 GHz wiggler is sought. At this energy the quality and phase stability of the bunchlets can be well established.

6 REFERENCES

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