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A RF-LINAC, FEL Based Drive Beam Injector for CLIC

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Abstract

We describe a means of producing a train of 40 kA pulses of 3 ps duration as the drive beam for CLIC using an RF linac driven free electron laser (FEL) buncher. Potential debunching effects are discussed. Finally we describe a low energy test experiment.

1 Introduction

Among the many technological challenges of the CLIC two-beam accelerator scheme [1] to design a TeV linear collider of electrons and positrons one of the most difficult is the generation of the drive beam. The CLIC drive beam is composed of 40 kA bunchlets of $\simeq$ 3 ps duration (σ_0) with a total charge of $\simeq$ 160 nC. Eleven bunchlets are repeated at a frequency of 30 GHz to form a pulse train that is repeated 4 times at a frequency of 352 MHz to form a macropulse. The macropulses must be generated at a repetition rate of $\simeq$ 2 kHz. These features are summarized in Table 1.

Clearly the most difficult feature of producing the drive beam is the formation of such high charge, picosecond duration bunchlets at energies $\leq$ 50 MeV. As it is unlikely that the bunchlets can be generated directly from a cathode with the desired waveform, one must consider other strategies, all of which involve one or more stages of bunch compression.

The consequences of the bunching properties of a high gain FEL have been investigated theoretically [2] and demonstrated experimentally [3], but the bunching of the beam current per se has never been measured. Recently Shay et al. [4] have proposed the use of a high gain FEL driven by a 15 MeV, 2–3 kA linear induction accelerator to generate the CLIC drive beam. Here we extend to higher currents the ELFA high gain FEL [5] with wave guide slippage control driven by a 10 MeV superconducting RF linac operating at 352 MHz. In particular we propose to furnish the drive beam for CLIC with an amalgam of magnetic switching, rf-accelerator and FEL technologies. The use of a radio frequency linac facilitates the control of energy spread in the beam and makes it more practical to extend beam energy up to 40 MeV if desirable. The use of a low frequency rf-accelerator avoids several technological difficulties related to voltage regulation in induction linacs [4,6]. Moreover, the 352 MHz linac is easily phased locked to the main drive beam linac.

At the entrance to the 30 GHz FEL buncher which compresses the beam current into 40 kA, 3 ps bunchlets, we require a beam of $\simeq$ 4 kA at $\simeq$ 20–30 MeV. The beam train begins with a high voltage, high current electron gun. One such gun with suitable characteristics is the SNOGUN [6] presently under construction by Science Research Laboratory and UCLA. SNOGUN consists of a small thermionic cathode generating a 400 A, 1.5 ns beam in a 1.25 MeV induction stack driven with SNOMAD magnetic pulse compressors. Beam extraction is controlled with a grid driven by ferrimagnetic shock lines. At the exit of the electron gun, rf bunching cavities or an FEL pre-buncher can be used to compress the beam to a 4 kA, 120 ps pulse prior to its acceleration to 20–30 MeV in cryogenically cooled, high field 352 MHz cavities. The 20 MeV beam is injected with a 30 GHz signal into a waveguide inside a short, high field wiggler. Operating with beam high currents, the FEL process leads to high gain of the 30 GHz signal and rapid bunching of the beam. The termination of the FEL well before saturation maximizes the compression of the beam current and minimizes the energy spread to yield the peak currents and waveform desired for CLIC. As the initial 1.5 ns pulse can only yield 4 bunchlets the entire pulse train is produced by three lines running in parallel. The subsequent rapid acceleration prevents space charge debunching. A schematic of this scheme using a FEL pre-buncher is shown in Fig. 1.

2 The high gain FEL as a buncher

When a beam traverses the FEL wiggler of period, λ_w, radiation is generated at the resonant wavelength λ_s. As the signal grows the pondermotive potential created by the wiggler field and the radiation bunches the beam electrons periodically on the wavelength scale of the resonant (sometimes called optical) wavelength. The current compression due to the FEL action can be computed from the bunching parameter, b, which is the ensemble average

$$b = | < e^{-i\theta} > | \tag{1}$$

where θ_i is the phase of the i-th electron with respect to the radiation frequency. For an unbunched beam, $b = 0$ while for a beam bunched to a delta function of current, $b = 1$. The strong FEL bunching is evidenced from the fact that when the gain saturates the bunching factor reaches a maximum $b_{max} = 0.8$ regardless of the actual values of the initial current, λ_w, or λ_s.

The gain of the FEL and the speed of the bunching process is described by the BPN universal scaling parameter [2], ρ;

$$\rho = \frac{1}{\gamma}\left(\frac{a_w \omega_p}{4ck_w}\right)^{1/3} \propto \frac{J^{1/3} B_w^{2/3} \lambda_w^{4/3}}{\gamma} \tag{2}$$

Peak bunchlet current, I_{peak}	40 kA
Bunchlet rms duration	3 ps
Charge per bunchlet, Q	160 nC
Bunchlet spacing	1 cm
Bunchlet frequency	30 GHz
Bunchlets per pulse	11
Pulse frequency	352 MHz
Pulses per macropulse	4
Macropulse frequency	1500 Hz

Table 1: Features of the CLIC Drive Beam

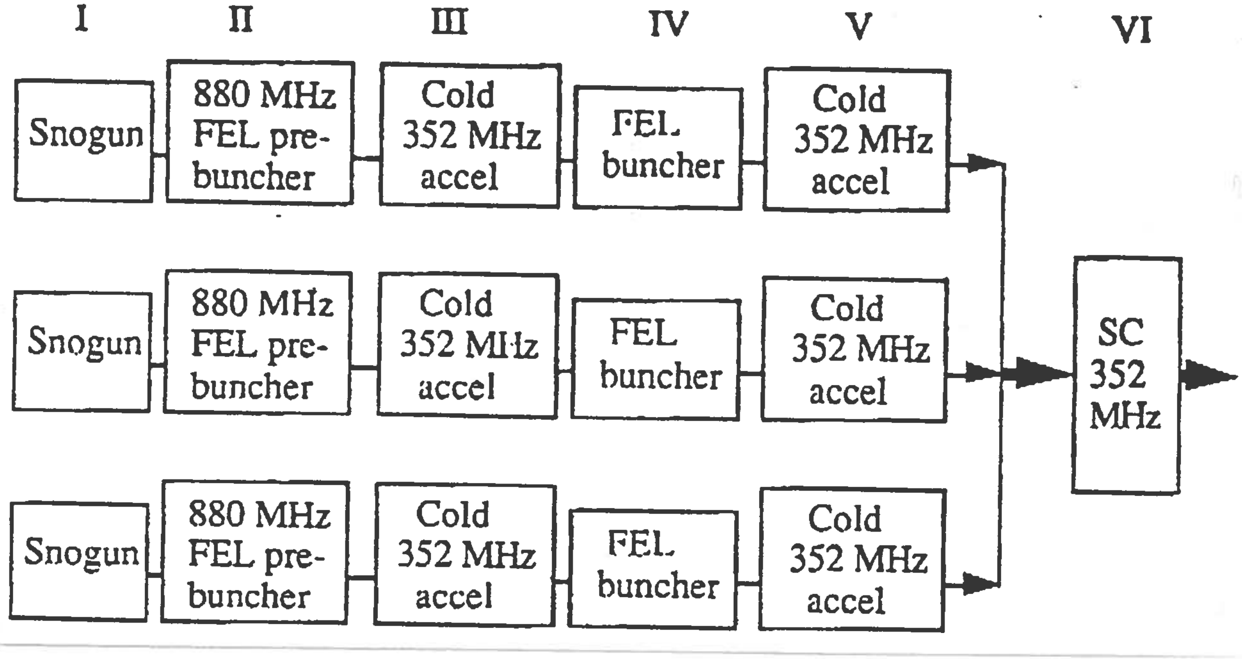


Figure 1: The proposed generator chain for the CLIC drive beam: Section I - 1.25 MeV; 1.2 ns; 500 A; Section II - 1.25 MeV; 1 bunch @ 120 ps; 5 kA; Section III - 25 MeV; 1 bunch @ 120 ps; 5 kA; Section IV - 25 MeV; 4 bunches @ 3 ps; 50 kA; 30 ps spacing; Section V - 50 MeV; 4 bunches @ 3 ps; 50 kA; 30 ps spacing; Section VI - 3 GeV; 12 bunches @ 3 ps; 50 kA.

where γ is the usual relativistic factor, ω_p is the non-relativistic plasma frequency, a_w is the dimensionless vector potential of the wiggler, k_w is the wiggler spatial frequency, B_w is the wiggler peak field and J is the beam current density.

$$a_w \simeq 0.66 B_w(Tesla)\lambda_w(cm) \tag{3}$$

$$k_w \simeq \frac{2\pi}{\lambda_w} \tag{4}$$

We note the experimentally verified feature of the high gain FEL, namely that the rate of the bunching action is proportional to $\rho\lambda_w$; hence the bunching actually proceeds more rapidly as the input current increases. In fact, in the experiment of ref. [3] the bunched current inferred from the well–verified simulations of the experiment was $\simeq 10kA$ (though this feature was never measured). It is this characteristic that makes the FEL buncher so attractive in comparison with other bunching schemes when the final peak value of the bunched current must be extremely large as in the case of the CLIC drive bunches. If the initial current pulse is several optical wavelengths long, the output current from the FEL will be a train of high current bunchlets spaced at the optical wavelength. With respect to the requirements of the CLIC drive beam, achieving a precisely controlled bunchlet spacing at the desired interval corresponding to 30 GHz is a natural consequence of FEL action.

Another feature of the FEL that compares favorably with respect to other bunching schemes is that the length over which bunching occurs scales favorably (increases linearly with increased beam energy). The FEL action does, however, induce an energy spread in the beam that is proportional to the gain. By terminating the wiggler before the FEL process saturates one can a) maximizes current multiplication, b) keep the induced energy variation small, and c)minimizes wiggler length.

3 Potential limiting phenomena

We now turn our attention to phenomena that can limit the performance of the FEL bunching process:

a) energy spread at the entrance to the wiggler,

b) loss of the radiation field via diffraction,

c) transverse and longitudinal space charge debunching.

3.1 Effects of energy spread

With respect to the intrinsic energy spread that is produced by the acceleration process upstream of the buncher the FEL compares well with other techniques. Quantitatively, we expect the FEL to be insensitive to instantaneous energy spreads and variations as long as

$$\left(\frac{\Delta\gamma}{\gamma}\right)_{accelerator} < \rho \tag{5}$$

As the FEL (or rf-cavity) pre–buncher in Fig. 1 is followed by an accelerator section that increases the mean beam energy by a factor of $\simeq 5$, this requirement is easily satisfied especially as the wiggler is actually truncated before saturation is reached. Moreover, even the strong super-radiant regime can be used in our scheme. In this case the sensitivity of the FEL is further reduced with respect to both the instantaneous energy spread or to the energy variation in the beam.

3.2 Loss of the radiation field via diffraction

In optical FELs using very low emittance beams the gain can be reduced and the bunching speed decreased if the radiation diffracts out of the electron beam too rapidly. In our case this consideration does not apply as the radiation is confined to the region close to the beam by the waveguide that we use to control the slippage of the radiation field with respect to the electron beam. The effectiveness of the waveguide in eliminating the degradation of performance due to diffraction is displayed by the results of a full three dimensional simulation with the code GINGER [8] that includes the effects of longitudinal space charge forces.

In figure 2 and 3 we show the GINGER simulations with the output power and bunching as a function of the length of the wiggler (figure 2) and also the histogram of the current and the electron longitudinal phase–space in a wavelength (figure 3). Note in figure 2 the link between the FEL gain and the bunching mechanism and the strong bunching action that derives from the combination of the dispersive path in the wiggler and the strong ponderomotive potential.

Thus we are left with space charge as the only potentially deleterious effect.

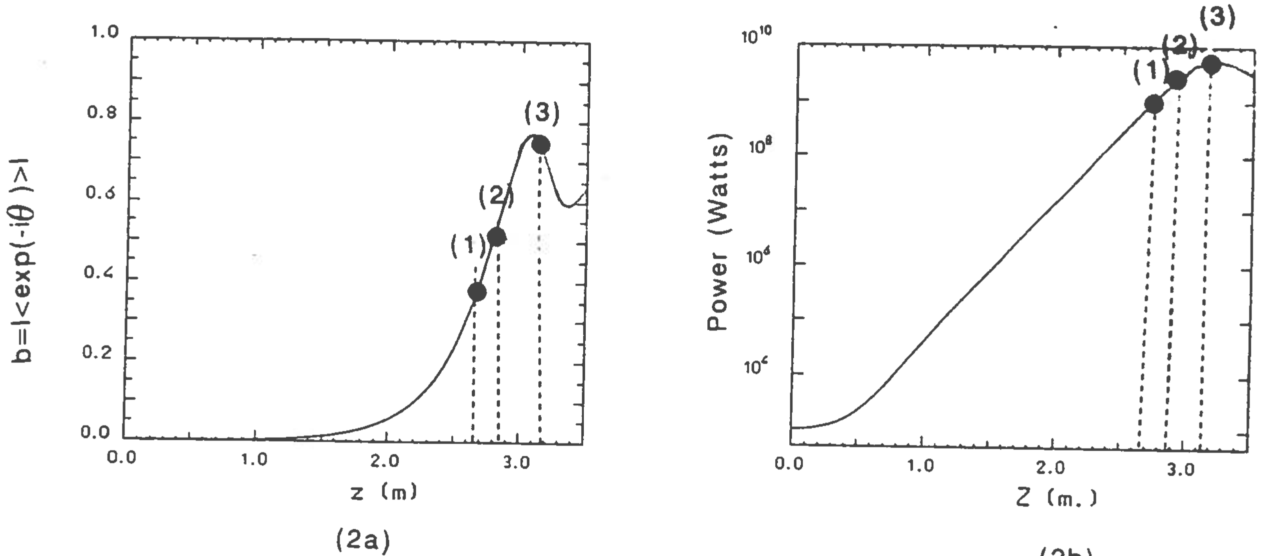
Peak bunchlet current, I_{peak}	4 kA
Radiation Wavelength, λ_s	1 cm
Beam Energy	9.5 MeV
Wiggler Wavelength, λ_w	24 cm
Wiggler Field, B_w	2.5 kG
FEL Parameter, ρ	0.13
Waveguide Heigth, b	2.5 cm
Normalized Beam Emittance, ϵ_n	0.1 π cm rad
Input Power, P_0	1 kW
Output Power, ρP_{beam}	$\simeq$ 5GW
Saturation Length Z_{sat}	$\simeq$ 3.5m

Table 2: Parameters of the GINGER runs

3.3 Transverse space charge effects

To begin our analysis we consider first the problem of the transverse space charge. Outside the bunched beam of radius R the radial electrostatic field, E_r, is

$$E_{r,peak}(r) = -\frac{I_{peak}}{2\epsilon_0\pi c\beta r} = \frac{60 I_{peak}(A)}{r(m)} MV/m \qquad (6)$$



(2a)

(2b)

Figure 2: GINGER Simulation of the FEL - parameters in table 2.
We show the bunching parameter b (2a) and the output power in Watts, in a logaritmic scale (2b), as a function of the length of the wiggler, $Z(m)$.

For an explanation of the marked points refer to figure 3.

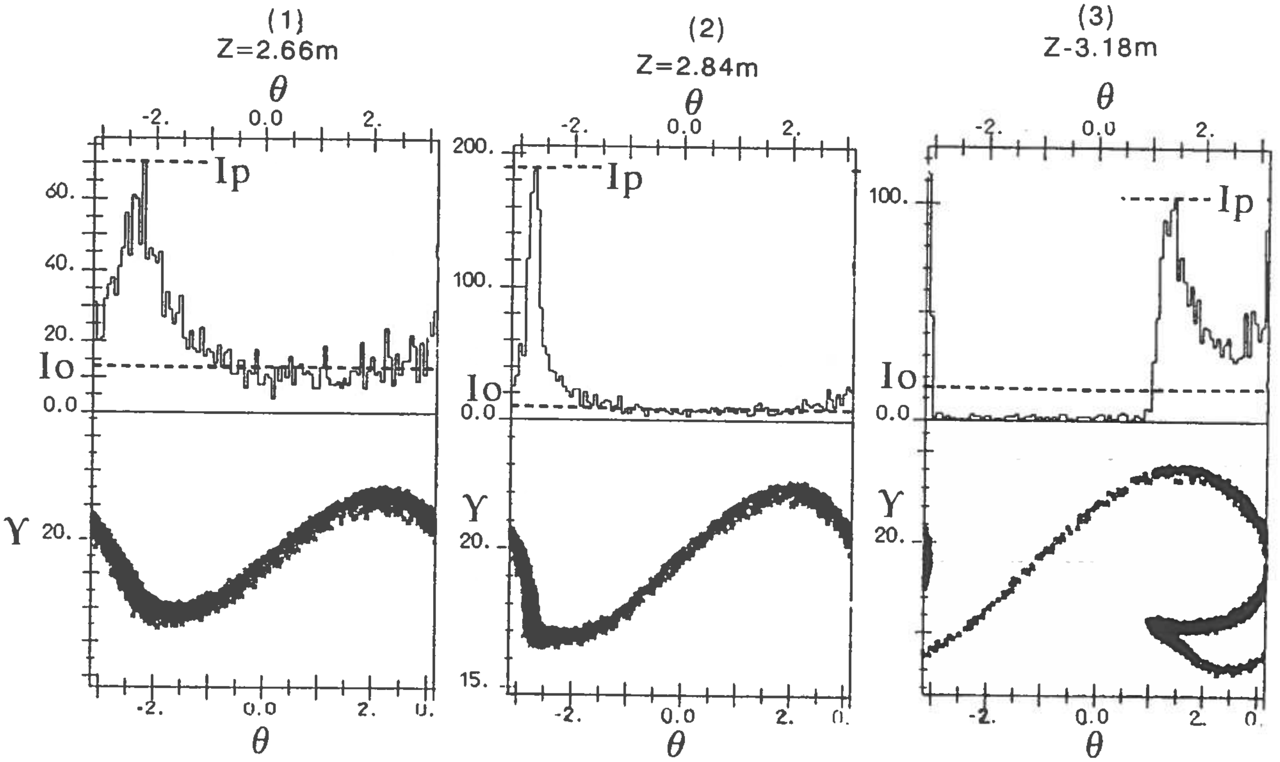


Figure 3: Phase Histogram, showing the electron current in a wavelength (top).
Electron Distribution in the Longitudinal Phase Space (bottom). I_0 is the average input electron current and I_P is the peak electron current. Note the strong peak current that can be obtained if one stops the wiggler at the proper point (Z=2.84m).
The outputs shown here are at the points marked in figure 2.

In eq. (6) c is the speed of light, ϵ_0 is the permittivity of free space, and β is the velocity of the electrons, v, divided by c. For the 40 kA CLIC bunchlet at 20 MeV with an rms radius of 3 mm the radial electric field evaluated at the edge of the beam is $\simeq 800 MeV/m$. Thus transverse space charge would be disastrous were it not for the fact that a relativistic beam carries its own extremely strong, azimuthal focussing field, B_θ,

$$B_\theta(r) = \frac{\mu_0 I_{peak}}{2\pi r} = \frac{I_{peak}(A)}{r(cm)} Gauss \tag{7}$$

Once we include this pinch field in the Lorentz force equation we find that the relativistic electrons experience very little radial force,

$$F_r = e(E_r - vB_\theta). \tag{8}$$

Noting from eq. (6) and eq. (7) that

$$B_\theta = \frac{v}{c} E_r, \tag{9}$$

we obtain the well known result

$$F_r = eE_r\left(1 - \frac{v^2}{c^2}\right) = \frac{1}{\gamma^2} eE_r. \tag{10}$$

Recalling that 1Gauss $\simeq 3 \times 10^4$V/m, we can see that outside of the wiggler at 20 MeV even a 40 kA bunchlet can be confined radially against space charge expansion by a magnetic field equivalent to a B_θ of only a few tens of Gauss. In fact, a larger field is actually needed to prevent the beam from expanding due to its finite emittance.

The relative effects of the emittance, ϵ, and transverse space charge on the beam as it propagates in the z direction can be evaluated both outside of and within the wiggler through the use of the envelop equation for the rms radius of the beam,

$$\frac{d^2R}{dz^2} - \frac{\epsilon^2}{R^3} + \frac{U}{R} + \langle \frac{K_\beta^2 R^2}{R} \rangle = 0 \tag{11}$$

The transverse self-fields of the beam are described by potential U and the external focussing by the term K_β. If the external focussing can be described by an harmonic potential with betatron frequency k_β, the ensemble average in the last term is reduced to the simple product $k_\beta^2 R$. In the wiggler the betatron frequency is

$$k_\beta = \frac{2\pi}{\lambda_w} = \frac{2\pi a_w}{\sqrt{2}\lambda_w \gamma} \tag{12}$$

In the absence of space charge neutralization from a background plasma the potential U may be expressed in terms of the Alfvén current as

$$U = -\frac{I(kA)}{17(kA)\gamma^3} \tag{13}$$

The envelope equation implies a unique equilibrium radius for the beam, R_e,

$$R_e = R_0(f + \sqrt{1 + f^2})^{1/2} \tag{14}$$

where $R_0 = \sqrt{\epsilon/k_\beta} = 6 \times 10^{-2}\sqrt{\epsilon(mrad)/B(I)}$ is the equilibrium radius in the absence of space charge and

$$f = \frac{U}{2\epsilon K_\beta} = \frac{U\gamma}{2\epsilon_n K_\beta} = \frac{10^{-4} I(kA)}{B_w(T)\epsilon_n \gamma} \tag{15}$$

In eq. (15) we have introduced the normalized emittance, ϵ_n, which is equal to $\gamma\epsilon$. From eq. (14) and eq. (15) we can see that the transverse space charge effects can be ignored when

$$\epsilon_n > \frac{U\gamma}{2k_\beta} = \frac{10^{-4} I(kA)}{\gamma \beta_{||}} \tag{16}$$

To satisfy the high gain FEL conditions, the phase area of the electron beam should be smaller than that of the radiation; i.e.,

$$\epsilon_n < \frac{\lambda_s \gamma}{2\pi} \tag{17}$$

For a 40 kA bunchlet at 20 MeV, B_w = 0.66T both eq. (16) and eq. (17) will be satisfied when

$$1.5 \times 10^{-4} mrad < \epsilon_n < 6.2 \times 10^{-2} mrad \tag{18}$$

This condition is easily satisfied for our proposed injector for the CLIC drive beam; we can choose a value $\epsilon_n = 2 \times 10^{-3}$ m rad so that the beam has a convenient radius ($\simeq 3$ mm) with respect to the heigth of the waveguide. From this discussion we conclude that the neglect of transverse space charge effects in the GINGER simulation upon which we would base a final design is justified.

3.4 Longitudinal space charge debunching

The potential difficulties arising from longitudinal space charge forces are more complicated to analyze as the net force depends on the geometry and charge distribution in the bunch and on the external boundary conditions. Fortunately with respect to the FEL action, in the wiggler all these dependences have been fully included in the GINGER simulation which was shown in figure 2 and 3. Therefore, we need to focus our attention on the debunching at the output of the wiggler.

Following ref.[4] we quote the calculation [9] of the longitudinal electric field, E_z, of a relativistic beam with charge distribution, n_e, in a long conducting pipe of radius b. Up to terms of order $ln(b/R)$

$$E_z = -\alpha \frac{dn_e}{dz} \tag{19}$$

where

$$\alpha = \frac{R^2}{4\pi\epsilon_0\gamma^2} \tag{20}$$

Assuming the bunchlet to have a Gaussian charge distribution with width σ_0 and total charge Q,

$$n_e = \frac{Q}{\pi R^2} \frac{1}{\sqrt{2\pi}\sigma_0} exp\left(\frac{-z^2}{2\sigma_0^2}\right) \tag{21}$$

One can easily evaluate the maximum value of E_z, which is obtained when $z = \sigma_0$;

$$E_{z,max} = \frac{1}{4\pi\epsilon_0} \frac{Q}{\sqrt{2\pi e}\gamma^2\sigma_0^2} \tag{22}$$

This formula can be readily understood as the field produced by a point charge $Q/(2\pi e)^{1/2}$. The factor γ^2 comes from the Lorentz transformation from the beam frame into the laboratory frame; the factor $(2\pi e)^{1/2}$ derives from the Gaussian shape. Putting in physical quantities, we have

$$E_{z,max} = 8 \times 10^{-6} \frac{I(A)\lambda_s(m)}{\gamma^2\sigma_0^2(m)} \tag{23}$$

where $I = Qc/\lambda_s$ is the average current over a optical wavelength. For our proposed scheme to produce a drive beam for CLIC, i.e., I = 4 kA, $\lambda_s = 10^{-2}$ m, $\sigma_0 = 10^{-3}$ m, and $\gamma = 40$,

$$E_{z,max} = 0.2MV/m. \tag{24}$$

Knowing $E_{z,max}$ we can estimate the energy spread induced by the space charge after the bunch travels a distance L out of the wiggler. From Newton's law:

$$\left(\frac{\Delta\gamma}{\gamma}\right)_{sc} \simeq \frac{eE_zL}{\gamma mc^2} \simeq \frac{2E_z(MV/m)L(m)}{\gamma} \tag{25}$$

In our case,

$$\left(\frac{\Delta\gamma}{\gamma}\right)_{sc} \simeq \frac{0.4}{40}L = 10^{-2}L(m) \tag{26}$$

The space charge induced energy spread must be added to that generated by the high gain FEL action, namely,

$$\left(\frac{\Delta\gamma}{\gamma}\right)_{FEL} \simeq \rho, \tag{27}$$

where ρ is the FEL scaling parameter of section II. For our parameters ρ is of order 10^{-2} . If the energy spread that can be tolerated in the input sections of the rf linac that raises the beam energy from 20 MeV to 3 GeV is in the range from $5-10\%$, then eq. (26) implies that a drift of 5 to 10 m is tolerable. This distance is a reasonable length for the matching section from the wiggler to the front end of the drive linac. We must, of course, verify that the debunching of the current produced in the drift length L between the wiggler output and the next RF–cavity is also acceptably small.

The debunching length, L_D, is defined as the distance over the bunchlet doubles in length; i.e., $\Delta\sigma = \sigma_0$. In an experiment to verify the longitudinal effects of space charge we should have

$$\left(\frac{\Delta\gamma}{\gamma}\right)_{sc} \gg \left(\frac{\Delta\gamma}{\gamma}\right)_{FEL} = \rho \tag{28}$$

Inserting eq. (25) into eq. (28) we have

$$E_{z,max}(MV/m)L(m) \gg \frac{\gamma\rho}{} \tag{29}$$

For the CLIC buncher $L \gg 2$ m; as ρ scales as γ^{-1}, $E_{z,max}L$ will be independent of γ. Hence, we can test the CLIC drive beam buncher and all the relevant physics in a low energy experiment as we discuss below.

Regarding the debunching length we have:

$$\Delta\sigma = \Delta\beta L = \frac{\Delta\gamma}{\gamma^3}L = \frac{2E_z L^2}{\gamma^3} \qquad (30)$$

The debunching value L' is determined imposing $\Delta\sigma = \sigma_0 = 1\text{mm}$, i.e.,

$$L' = \sqrt{\frac{\sigma_0\gamma^3}{2E_z}} = 2.5\times 10^2\sqrt{\frac{\sigma_0^3\gamma^5}{I\lambda_s}} \qquad (31)$$

where E_z is given by equation 23. Inserting $E_z = 0.2MV/m$ and $\gamma = 40$, one obtains $L' = 12.6$m

If one assumes a 10 MeV beam as in the GINGER runs quote above, all the previous expression can be rescaled. To be precise

$$E_{z,max} \propto \frac{1}{\gamma^2} \simeq 0.8MV/m. \qquad (32)$$

$$\left(\frac{\Delta\gamma}{\gamma}\right)_{sc} = 8\times 10^{-2}L(m)\left(\propto\frac{1}{\gamma^3}\right) \qquad (33)$$

so that $\Delta\gamma/\gamma \leq 0.1$ if $L \simeq 1.25$m and the debunching length becomes $L' \simeq 2.3$m , $L \propto 1/\gamma^{5/2}$.

If these distances seem somewhat shorter than practical, one can increase the energy of the beam from 10 MeV to 20 MeV as in the previous example. A further increase to 40 MeV would abolish space charge effects for all practicall purposes. These features have been already confirmed by preliminary calculation performed with PARMELA for a beam expanding inside a solenoidal B field in otherwise free space. The PARMELA simulations assume the beam to have a uniform hard edge electron beam distribution, which certainly increases space charge effects at the beam boundary. Nevertherless for a 20 MeV we find a debunching length of 3m and at 40 MeV more than 30m. More detailed simulations including the effects of the Gaussian distribution of charge and of the beam pipe boundary conditions will be presented elsewhere.

Finally let us point out that the extension of FEL energy from 20 to 40 MeV with an RF–linac does not present any serious problem because the FEL scaling laws are such that the increase in γ can be compensated by increasing the wiggler period. This will be discussed in detail elsewhere. In addition, the longer wiggler period makes the construction of the wiggler easier.

4 Suggested test experiment at 10 Ampere and 2.5 MeV energy beam

All the bunching properties of the RF–linac driven FEL with waveguide control of slippage can be tested in a low energy, low current experiment. Novel features of this experiment include the measurement of the bunched current, slippage control in the FEL, and strong super-radiant behavior of the FEL. With the same wiggler as we would use with the full

20 MeV, 4 kA beam, the laser gain will be nearly the same as the gain scales as $\rho \simeq I^{1/3}$. If we decrease I by a factor 400 from 4kA to 10 A, we should simultaneously decrease the beam energy γ by a factor of 6.6, down to 2.5 MeV. Then the saturation length of the FEL amplifier will remain unchanged. Furthermore the low energy experiment allows us to test all the relevant properties of space charge debunching. Imposing that $(\Delta\gamma/\gamma)_{sc}$ is much longer than the intrinsic FEL linewidth ρ , i.e., $(\Delta\gamma/\gamma)_{sc} > \rho$ and using the previous expression we have

$$L(m) \gg \frac{\gamma^3 \sigma_0^2 \rho 10^5}{2\lambda I} = 10^2 \rho \tag{34}$$

For the suggested parameters for the experiment:
$\gamma = 6$, I $= 10$ Amp, $\sigma_0 = 1$mm, $\lambda = 1$cm, the FEL parameter, $\rho = 2 \times 10^{-2}$;
hence, for distances L exceeding 1 m space charge effects will dominate the debunching process and will be readily distinguishable from debunching due to the FEL induced energy broadening.

Peak bunchlet current, I_{peak}	10 A
Radiation Wavelength, λ_s	1 cm
Beam Energy	2.5 MeV
Wiggler Wavelength, λ_w	12 cm
Wiggler Field, B_w	1.8 kG
FEL Parameter, ρ	0.018
Waveguide Heigth, b	1.7 cm
Normalized Beam Emittance, ϵ_n	0.1 π cm rad
Input Power, P_0	1 kW
Output Power, ρP_{beam}	$\simeq$ 0.5 MW
Saturation Length Z_{sat}	$\simeq$ 5 m

Table 3: Parameters of the FEL Test

5 Conclusions

We have shown that the RF–FEL buncher appeas to be a promising scheme to provide the CLIC drive beam. Issues related to space charge can be made negligeble by the appropriate choice of energy at the input to the wiggler. Finally we have described the characteristics of a low current, low energy test experiment that would demonstrate all the relevant physics of our proposed scheme.

6 Acknowledgements

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