ON USING A SUPERCONDUCTING LINAC TO DRIVE A SHORT WAVELENGTH FEL*

G. A. Krafft and J. J. Bisognano

Continuous Electron Beam Accelerator Facility
12000 Jefferson Avenue
Newport News, VA 23606

Summary

In order to determine the suitability of using a superconducting radio frequency (SRF) linac to generate XUV radiation, the beam dynamics in such a linac have been simulated using a vectorized two dimensional beam breakup code, TDBBU. The energy spread and emittance of the accelerated beam are determined as a function of current for a linac like CEBAF and for a linac optimized for high peak currents. The results indicate that there are significant improvements in transverse emittance growth possible by going to lower RF frequencies and by utilizing BNS phasing in the accelerating cavities.

In the first section of this paper the simulation is described. Next, the transverse and longitudinal wakes typical in superconducting cavities are discussed. The results of the simulations are given, followed by a comparison of a linac driven FEL and a typical storage ring driven FEL. The conclusion of the work is that the former scheme looks promising because higher average power is possible.

Description of the simulations

The simulation code TDBBU[1] has been used to calculate the intrabunch collective effects since they degrade the bunch properties at high peak currents. The code neglects changes in the electron's longitudinal coordinate but follows the transverse phase space coordinates and the longitudinal momentum of the electrons. Electrons are tracked through a linac lattice. In addition, at the cavity and drift positions of the lattice, backward propagating wake functions are used to update the tranverse and longitudinal momenta. The form of the wake function as a function of τ is essentially arbitrary to the simulation.

Macroparticles are loaded with a uniform spacing in the longitudinal direction. A nonuniform bunch is simulated by changing the charge in the macroparticle as a function of the longitudinal coordinate. This approximation is reasonable as long as there is no longitudinal motion within the bunch, i. e. the bunch is relativistic, and as long as the instability generated by the wake occurs on distance scales long compared the spacing of the macroparticles.

In all the results to be reported here, the transverse load is the standard uniform elliptical load with a given emittance, the α and β functions at injection being chosen to match the focusing lattice of the accelerator. In most cases an offset is introduced at injection to initiate the instability.

A run involving 1500 machine elements and 3000 macroparticles takes about 15 CRAY 1 minutes.

Effect of the Longitudinal Wake

The stored energy in the superconducting cavity is

$$U = \frac{QV^2}{R\omega_0}$$

where V is the voltage gained when an electron traverses the cavity on crest, R/Q is the shunt impedance of the cavity, and $\omega_0/2\pi$ is the cavity frequency. The total energy extracted from the cavity by a bunch with total charge q is

$$u = qV.$$

The dimensionless quantity u/U is proportional to qk_f/V where k_f is the loss factor[2] for the fundamental mode

$$k_f = \frac{\omega_0}{4}\frac{R}{Q}.$$

In fact the relative energy spread scales the same way, if the loss factor is generalized to include all the longitudinal modes.

The longitudinal wake function, $W(\tau)$, quantifies the energy change experienced by a test particle following an exciting particle due to the longitudinal modes. By superposition, the energy error induced in the electron at time t is

$$\Delta E(t) = e\int_{-\infty}^{t} I(t')W(t-t')dt' = eq\int_{-\infty}^{t} \hat{n}(t')W(t-t')dt'$$

where $\hat{n}$ is the unit normalized distribution $\hat{n}(t) = I(t)/q$ and e is the electron charge. By performing the proper averages one obtains

$$\sigma_E = \sqrt{\langle\Delta E^2\rangle - \langle\Delta E\rangle^2 - \langle t\Delta E\rangle^2/t_{rms}^2} \qquad (1)$$

where the phasing of the cavities is chosen to minimize the rms energy spread. This result may be expressed in terms of the total loss factor as

$$\frac{\sigma_E}{E} = F\frac{qk_{\|}}{V}$$

where F is a form factor depending only on the form of the longitudinal wake and the bunch longitudinal density and $k_{\|}$ is the total loss factor[2]. The F constants for several types of bunch profiles are given in Table 1.

Longitudinal Distribution		F	σ_E
Uniform	$W(\tau) = A$	0	0
Parabolic	$W(\tau) = A$	0.05	$0.03eqA$
Gaussian	$W(\tau) = A$	0.08	$0.09eqA$
Uniform	$W(\tau) = B\tau^{-1/2}$	0.07	$0.09eqB/L^{1/2}$
Parabolic	$W(\tau) = B\tau^{-1/2}$	0.15	$0.15eqB/L^{1/2}$
Gaussian	$W(\tau) = B\tau^{-1/2}$	0.19	$0.20eqB/\sigma^{1/2}$

Table 1 Energy Spread for Various Wake Functions

Accelerator Configurations

Two accelerator configurations were simulated in this study. The first configuration, summarized in Table 2, has parameters corresponding to the present CEBAF accelerator. In addition

*This work was supported by the United States Department of Energy under contract DE-AC05-84ER40150.

to a longitudinal wake of 10 V/pC and a transverse wake of 6 V/pC cm^2 for a CEBAF cavity, the effective wakes in Table 2 include contributions from vacuum chamber discontinuities in the CEBAF design.

The second configuration, given in Table 3, represents a machine designed explicitly for high peak current operation as an FEL driver. The main features distinguishing such a linac from the CEBAF linac are:

- Lower operating frequency (350-500 MHz)
- Smooth vacuum chambers to avoid wake effects
- External termination of Higher Order Mode loads
- No recirculation to avoid multipass BBU instability

In addition, it is likely that some form of energy recovery would be attempted in order to take advantage of the high efficiency of the superconducting cavities and to avoid excessive power usage. Energy recovery does not affect the results of the calculations since bunch properties at the wiggler depend only on wakes generated on the first pass through the linac.

Frequency	1500	MHz
Injection Energy	45	MeV
Final Energy	4	GeV
Injection Emittance	1π	μm rad
Effective Transverse Wake	30.0	V/pC cm^2 per cavity
Effective Longitudinal Wake	41	V/pC per cavity
Bunch Length	2.2	psec

Table 2 Parameters in CEBAF Accelerator Simulation

Frequency	350	MHz
Injection Energy	10	MeV
Final Energy	1	GeV
Injection Emittance	1π	μm rad
Transverse Wake	0.8	V/pC cm^2 per cavity
Longitudinal Wake	7	V/pC per cavity
Bunch Length	22	psec

Table 3 Parameters in Driver Accelerator Simulation

The CEBAF lattice has constant focal length on the first pass and the driver lattice has constant focal length throughout. For concreteness we assume that the driver scenario has single cell 350 MHz cavities which achieve a total gradient of 5 MV/m. The injected normalized *rms* emittance for the beam is $1\pi \times 10^{-6}$ m rad (see Eqn. (2) below). Using Eqn. (1) the energy spread is estimated as a function of bunch charge for CEBAF and for the driver. In order to retain an energy spread less than .1% the bunch charge must be limited to 10^9 electrons for CEBAF, but the limit for the driver is about 10^{10} electrons.

Simulation Results

In Fig. (1) the effect of the longitudinal wake is given by plotting the energy error and time of the macroparticles as they leave CEBAF after acceleration. The energy error ΔE is the difference between the actual energy and the energy that the synchronous particle would have at zero current. The phasing of the cavities has been chosen to minimize the *rms* energy spread of the emerging beam. The peak current in the simulation was 300 A, the bunch shape was parabolic, and the longitudinal wake was proportional to $\tau^{-1/2}$. The energy spread is consistent with Eqn. (1).

In Fig. (2) the transverse position and time are plotted for the bunch macroparticles. The transverse wake causes the familiar distortion of the bunch into a banana shape. In Fig. (3) a tranverse phase plot of the emerging particles is presented, along with a zero current result in Fig. (4). The emittance of the bunch has effectively grown with current due to the transverse instability. The growth is quantified in our work by using the normalized rms emittance

$$\epsilon^n_{rms} = \sqrt{\langle P_x^2 \rangle \langle X^2 \rangle - \langle P_x X \rangle^2}/mc \qquad (2)$$

where P_x is $p_x - \langle p_x \rangle$, X is $x - \langle x \rangle$, m is the electron rest mass, and c is the velocity of light.

In Figs. (5) and (6) emittance is plotted against the peak current for several bunch lengths. In Fig. (5) the plot is for the nominal CEBAF parameters. In Fig. (6) the plot is for the driver configuration. If the cavities are phased in the way recomended by Balakin, Novokhatsky, and Smirnov[3] the effect of the transverse instability is reduced in several simulations that have been performed. Since emittance growth becomes a problem only at currents where energy spread is already excessive, the gains from BNS phasing are helpful only for relatively long bunches ($L > 6$ psec for CEBAF or $L > 60$ psec for the driver). Otherwise, the main limitation on bunch charge is due to the energy spread requirement in the FEL.

Since the maximum bunch charge in the driver is 2700 pC (corresponding to 180 A peak current) and the average power is limited, a maximum bunch repetition rate is obtained. For the overall continuous power into the accelerating cavities to be less than 20 kW, the bunch repetition frequency must not exceed 3 MHz. A storage ring-bypass scheme has been proposed as a coherant x-ray source at Berkeley[4]. The results of this proposal of most interest to us are an average power of .3 W at 400 Å, a peak power of 150 MW, and a radiation pulse length of 50 psec. The rather low average power is due to the fact that the beam is stored for a full damping time of the storage ring before passing through the FEL again. The comparable numbers for the optimized driver are an average power of 400 W, a peak power roughly the same as above, and a radiation pulse length of 20 psec, the main advantage being that the bunches can come much more frequently in the SRF linac case. It seems that the SRF driver compares favorably to the Berkeley proposal. However, without some form of energy recovery, the facility power is quite a bit larger than the storage ring proposal.

Conclusion

In this paper a superconducting linac driven FEL has been considered. It was shown that such a scheme can produce beams suitable for the generation of short-wavelength coherant radiation. The emittance growth from the accelerator and the energy spread of the beam have been computed as a function of current. In contrast to the situation in normal conducting linacs, superconducting linacs are dominated by the longitudinal wake effects instead of transverse wake effects. It should be emphasized that a self-consistent calculation has been done, i. e. the collective effects have been included in the estimates of linac performance, and the resulting beam quality is good in parameter regimes of interest. For radiation source drivers care should be taken to insure that the vacuum chamber is smooth in order to reduce the wake fields.

Acknowledgement

Discussions with B. Yunn are gratefully acknowledged.

References

[1] G. A. Krafft and J. J. Bisognano, *Proc. 1987 Particle Accelerator Conference*, IEEE Catalog No. 87CH2387-9, pg. 1356

[2] P. B. Wilson, *Physics of High Energy Particle Accelerators*, AIP Conference Proceedings No. 87, pg. 450 (1982)

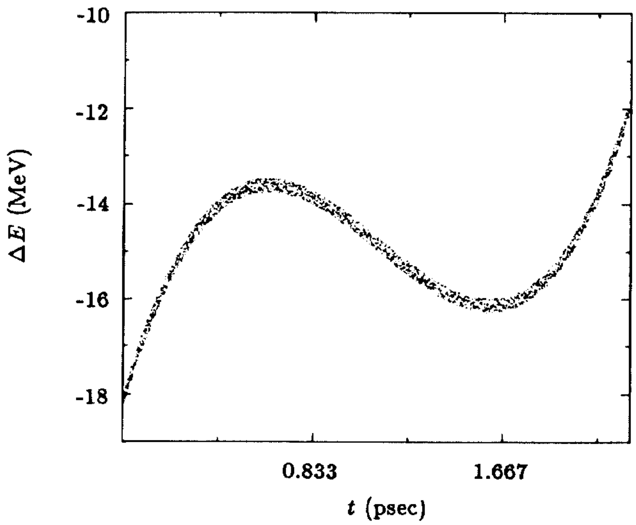

Fig. (1) Macroparticle Energy Error vs. Time at Exit from CEBAF

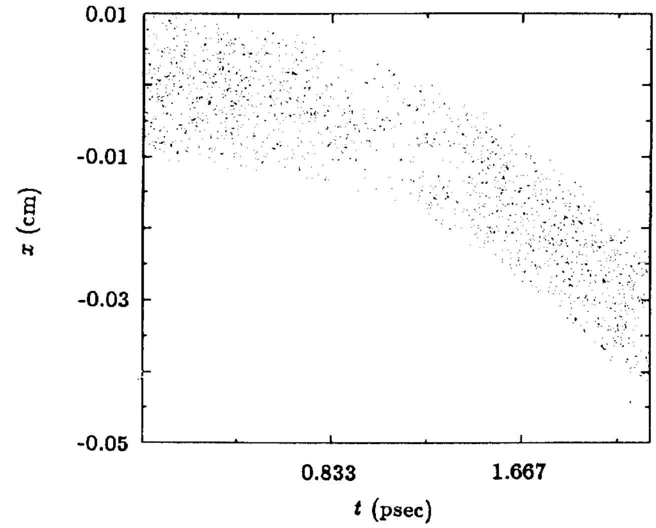

Fig. (2) Macroparticle Horizontal Position vs. Time at Exit from CEBAF

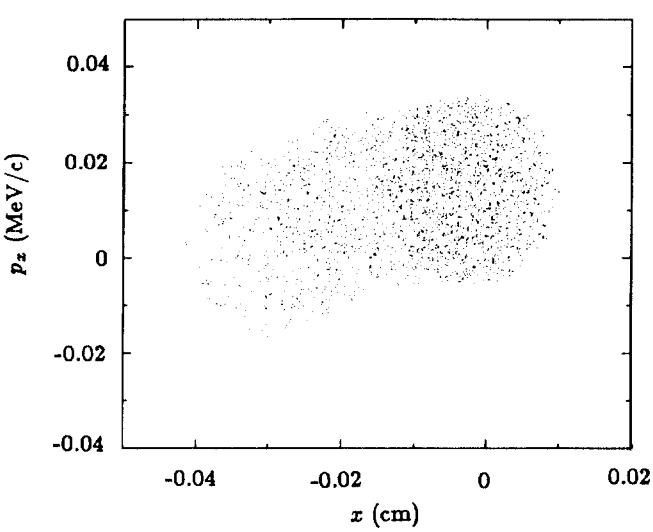

Fig. (3) Macroparticle Phase Space Plot at Exit from CEBAF

[3] V. Balakin, A. Novokhatsky, and V. Smirnov, *Proceedings of the 12th Int. Conf. on High Energy Accelerators*, Fermilab, pg. 119 (1983)

[4] J. Bisognano *et al.*, "Feasibility Study of a Storage Ring for a High-power XUV Free-electron Laser", *Particle Accelerators*, **18**, 223 (1986)

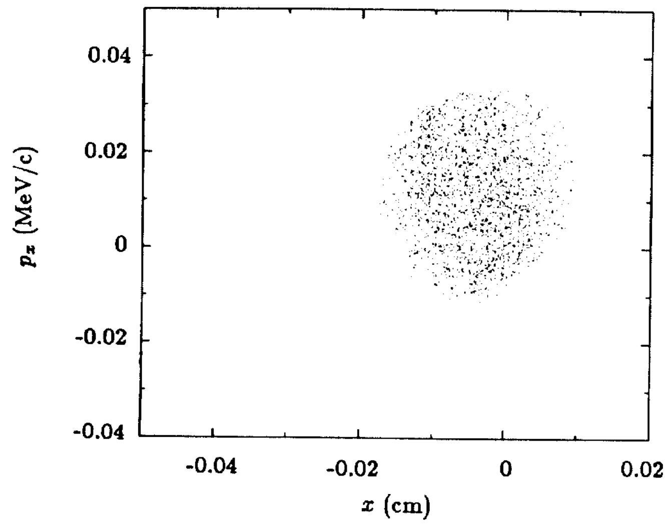

Fig. (4) Macroparticle Phase Space Plot at Exit from CEBAF, $I = 0$

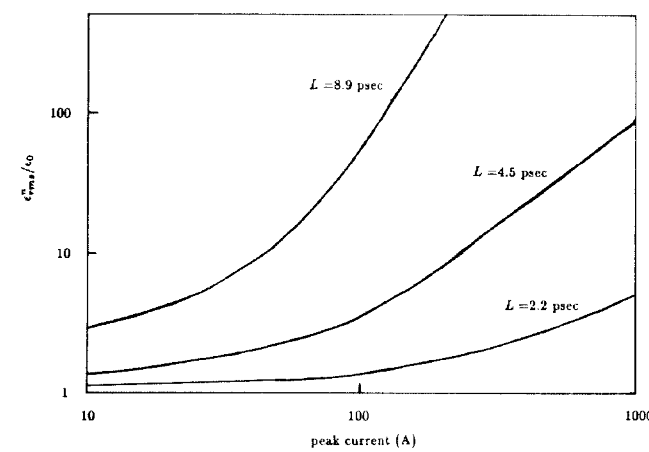

Fig. (5) Emittance vs. Current for CEBAF

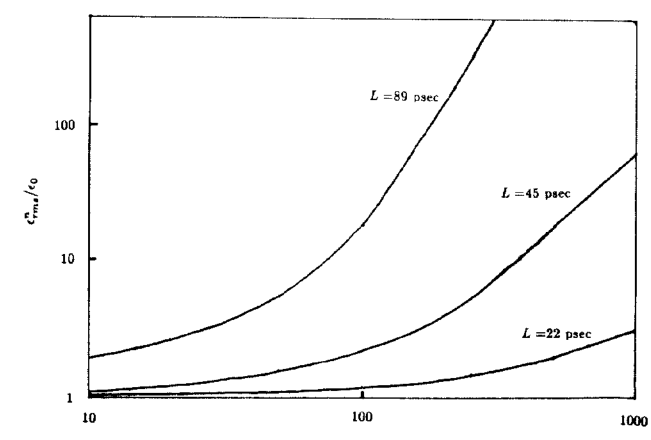

Fig. (6) Emittance vs. Current for Driver