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DESIGN CONSIDERATIONS FOR SIMULTANEOUS FEL AND NUCLEAR PHYSICS OPERATION AT CEBAF*

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Abstract

As conceived in a recent design study [1], electron beams of quite distinct character would be provided for nuclear physics experiments and FEL wigglers at CEBAF. When full nuclear physics operation begins, coordination between these two programs becomes critical. FEL operation requires electron bunches carrying charge of 120 pC at repetition rates of 2.5 and 7.5 MHz, whereas the nuclear physics users need a relatively small charge per bunch, $\sim$ 0.13 pC, but at a repetition rate of 1.5 GHz. To allow maximal operation of the FEL facility without interfering with CEBAF's primary mission of conducting nuclear physics research, the principal mode of operation should accelerate and deliver the two disparate beams simultaneously with negligible degradation of beam quality. Various RF power, RF control, wakefield, and beam transport questions that are encountered in designing for concurrent operation are discussed.

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Introduction

The Continuous Electron Beam Accelerator Facility (CEBAF) has been under construction since 1987 in Newport News, Virginia, to serve as a center for nuclear physics research. The CEBAF superconducting recirculating accelerator will provide electron beams at energies from 0.8 GeV to 4 GeV to nuclear physics experiments in three experimental halls. It is now being proposed that an additional high quality, continuous electron beam be provided for free electron laser research[1].

The CEBAF accelerator comprises a 45 MeV superconducting injector linac, two 400 MeV superconducting linacs (North and South), recirculation beamlines, and a beam extraction system. The electron beam can be recirculated five times to yield a beam energy of 4 GeV for three nuclear physics endstations at average currents up to 200 μA. Two FELs are envisioned as additions to this facility. The first will be driven by the 45 MeV output of the CEBAF injector, producing about 1 kW average power in the infrared. A second FEL will be driven by the 400 MeV output of the North Linac to provide deep UV at a similar average power.

Since the principal mission of CEBAF is nuclear physics research, FEL activities may interfere only minimally with this effort. Electron beams of quite distinct character would be provided for the nuclear physics experimental program and the FEL wigglers. FEL operation requires electron bunches carrying charges of 120 pC at repetition rates of 2.5 and 7.5 MHz, whereas the nuclear physics experimenters demand relatively low charge per bunch, 0.13 pC, but at a repetition rate of approximately 1.5 GHz. Although dedicated FEL operation for a modest fraction of beam time may be quite workable, a more transparent mode, which would accelerate and deliver the two disparate beams simultaneously with negligible degradation of beam quality, is desired to take full advantage of installed equipment.

CW superconducting linear accelerators permit great flexibility in bunch train configuration. Sequences of bunches can be spaced uniformly at essentially any multiple of the RF period; bunch trains can be of finite length or continuous; and charge can be modulated from bunch to bunch. A single linac, therefore, can serve a variety of users who have very different needs for bunch structure. Clearly, there are accelerator physics limitations on what distinct classes of bunches can be accelerated and delivered simultaneously. This issue has received some earlier attention [2] in the context of superconducting linear colliders, where parasitic operation for nuclear physics programs was considered. For the CEBAF accelerator, options for simultaneous FEL and nuclear physics beams are significantly constrained by installed rf power, induced wakefields, and beam transport complexity. Together, these issues provide a fairly well defined set of design choices which are described in the following.

Beam Transport and Extraction

In dedicated FEL operation, a relatively simple and compact transport optics with zero dispersion and negligible path-length variation could be designed for beam transport to the wigglers. Simultaneous operation demands a more complicated lattice to allow multiple beam transport and bunch compression while maintaining the high quality of both the nuclear physics and FEL bunches. In the injector region, the FEL beam drives an IR FEL, coexisting with a single nuclear physics beam. In contrast, extraction of the UV FEL beam at the end of the North linac will require careful manipulation of up to five nuclear physics beams at different energies from the five passes of acceleration.

With five classes of nuclear physics bunches (for five-pass operation) in the linac, the transport system must carefully peel off the FEL bunches to the UV wiggler. A broadband rf device could kick out the FEL bunches with little disturbance to the nuclear physics bunches, but power requirements appear excessive. A resonant device operating on a deflecting mode of a cavity has been suggested [3] and is under study. It requires some adjustment of the bunch structure to the nuclear physics endstations. A simple scheme using DC magnetic elements which separate beams by energy is chosen for the current proposal. The energy offset will be induced by timing the FEL bunches 25° off crest of peak acceleration, yielding a 10% energy difference with respect to the first-pass nuclear physics bunches.

The off-crest acceleration induces a head-to-tail rms energy spread for the FEL bunches which will be less than $1 \cdot 10^{-3}$, sufficiently small for the 50-period wiggler. The UV beam system has path-length tuning to provide a factor-of-two bunch compression to increase the peak current of the FEL bunches from 60 A to 120 A.

Beam Transport for the Infrared FEL

The electron beam from the CEBAF injection linac must be transported into the wiggler inside the IR FEL optical cavity with appropriate optical matching. The 45 MeV injector beam must be focused to a 0.3 mm radius spot at the wiggler. With a normalized beam emittance of 15 mm-mr, this implies fairly strong focusing to $\beta^* \approx 1.0$ m. Small or zero dispersion is also needed. Insertion into the optical cavity implies displacement of the beam from a straight transport. Concurrent operation with either the UV FEL or nuclear physics experiments implies the beam must be returned and matched for injection into the full-energy CEBAF linac. Figure 1 shows an appropriate transport line for the IR FEL.

The transport begins after the injection linac accelerating cavities, where the beam is bent 24° into an IR FEL bypass. The 24° beam drifts for ≈ 1.5 m into a reverse bend ($-24°$), where it then travels parallel to the initial linac, displaced horizontally by 0.7 m. An ~ 8 m, transport with five quadrupole magnets matches the beam into the 1.5 m wiggler. The wiggler is strongly focusing vertically with a matched $\beta_y^* = 0.5$ m. The matching conditions chosen for the transport line are $\beta_y^* = 0.5$ m at the entrance and exit of the wiggler, $\beta_x^* = 0.75$ m (Rayleigh length) at the wiggler center, and $\eta = 0$ at the wiggler center. The transport is designed to be betatron-matched to the injection line.

Simultaneous operation with the UV FEL and/or nuclear physics requires matched return of the beam into the main North Linac for further acceleration. The return optics from the FEL bypass are similar to the entrance optics: a ~ 6 m transport with five quadrupoles leading into a 24° bend, a 1.4 m drift, and a 24° reverse bend into the North Linac injection line. The return point is ~ 5 m before the North Linac injection chicane. Single quadrupole magnets have also been added to the center of each 1.5 m interdipole drift to improve dispersion matching. Both high-intensity FEL and nuclear physics bunches pass through the bypass in simultaneous operation. However, the nuclear physics bunches are not intense enough to induce lasing, and their interaction with the FEL optical beam is negligible.

The bypass is not isochronous; both the entrance and exit legs of the bypass contribute

≈ -0.30 m to the M_{56} matrix element. However, the contributions of the injection chicane can be tuned to cancel this and the beam can recover isochronicity before reaching the North Linac accelerating modules, thus preserving a necessary condition for simultaneous operation of the FEL and nuclear physics beams.

Beam Transport Requirements for the Ultraviolet FEL

The FEL electron beam from the CEBAF North Linac must be transported into the wiggler inside the UV FEL optical cavity with appropriate optical matching. To match the beam spot to the optical radius, the 400 MeV FEL beam must be focused to an rms spot size as small as 140 μm in radius in the wiggler. With an rms normalized emittance of 15 mm-mrad, this implies strong focusing to $\beta^* = 1$ m; to ensure maximum gain, the electron beam size is thus been matched to the optical beam size.

Small or zero dispersion is also needed. Simultaneous operation with nuclear physics applications implies the FEL beam must be separated from all (recirculated) nuclear physics beams with negligible operational impact. Additionally, the desire for high peak currents in some operating modes requires a means of varying M_{56} between 0 and -1 m to provide sufficient longitudinal compression of the FEL bunch. The UV FEL beam transport is shown in Figure 2.

A dipole–quad-triplet–dipole translation generates an achromatic, nearly isochronous ($M_{56} = 0.0013$ m) horizontal offset to an axis parallel to the linac axis. Along this axis, a vertical chicane centered in a symmetric insertion formed by a pair of quadrupole doublets provides the desired variation in M_{56}. This system provides $0 \leq M_{56} \leq 1$ m while holding the beam envelope functions external to the insertion fixed. A second achromatic, nearly isochronous dipole–triplet–dipole horizontal translation moves the beam onto the optical cavity axis, which is displaced from the bunch-compression chicane by 2/3 m to avoid interference between beam transport elements and the FEL optical cavity. Downstream of the second translation, a pair of quadrupole doublets provides matching of the transverse betatron functions into the wiggler. Following the wiggler, a single large angle dipole vertically diverts the FEL beam to a beam dump.

Simultaneous, transparent operation with nuclear physics requires additional manipulations of the recirculated nuclear physics beams. The proposed system assumes the FEL beam will be 10% lower in energy than the lowest energy nuclear physics beam. In this scheme the spreader structure which diverts the FEL beam to the bypass disperses all beams by energy. Nuclear physics beams are separated from the FEL using a system of septa and returned, via a system of chicanes, to the linac axis for recirculation. This initial chicane system causes a path-length increase for all beams. The increase can be compensated using recirculation arc doglegs for all but the lowest-energy beam. A second chicane system is employed to retard the lowest-energy beam still further. The individual chicane systems will make a negative nonzero contribution to the M_{56} for transport of each beam from linac to linac, which can be compensated by adjustment of the recirculation transport arc quadrupoles.

RF Power and Control

When a CW low-current beam for nuclear physics studies is operated concurrently with a high-current FEL beam (a high-current bunch every 200 bunches), the voltage seen by the low-current bunches looks like a saw-tooth with discontinuities synchronous with the arrival of the high-current bunches.

Following an earlier study [4] the change of the voltage of the fundamental accelerating mode from the beam load, ΔV, is found from

$$\frac{d^2\Delta V}{dt^2}+\frac{\omega_c}{Q_L}\frac{d\Delta V}{dt}+\omega_c^2\Delta V=-\frac{\omega_c}{Q_c}\frac{dV_B}{dt}$$

where $\omega_c = 2\pi f_c$ is the cavity angular frequency, Q_c is the unloaded quality factor of the cavity, Q_L is the loaded quality factor

$$Q_L=\frac{Q_c}{1+\beta},$$

where β is the coupling factor, $V_B(t) = Z_c I(t)$ is the beam-loading voltage, Z_c is the peak value of the cavity shunt impedance, and $I(t)$ is the beam current.

Integration yields

$$\Delta V(t)=-\int_{-\infty}^{t} e^{-\omega_c(t-t')/2Q_L}\cos(\hat{\omega}(t-t'))\omega_c\frac{Z_c}{Q_c}I(t')dt'$$

if $Q_L \gg 1$, and $\hat{\omega} = \omega_c\sqrt{1 - 1/4Q_L^2}$

If the beam current is

$$I(t') = \sum_{l=-\infty}^{\infty} I\tau\delta(t' - l\tau)$$

where τ is the time between the high-current bunches, the voltage error is

$$\Delta V(t) = -\omega_c\tau\frac{Z}{Q}Ie^{-\omega_c(t-[t/\tau]\tau)/2Q_L} \times \frac{\cos(\hat{\omega}(t - [t/\tau]\tau)) - e^{-\omega_c\tau/2Q_L}\cos(\hat{\omega}(t - [t/\tau]\tau) - \hat{\omega}\tau)}{1 + e^{-\omega_c\tau/Q_L} - 2\cos(\hat{\omega}\tau)e^{-\omega_c\tau/2Q_L}} \qquad (1)$$

where [ ] denotes the function giving the greatest integer less than its argument.

Using $R = 2Z_c$, the accelerator shunt impedance, in the subsequent formulas, and $\omega_c t/2Q_L \ll 1$ for the case of interest at CEBAF, one obtains

$$\Delta V(t) \doteq -\frac{R}{Q}Q_L I\cos(\hat{\omega}(t - [t/\tau]\tau)) + \pi N\frac{R}{Q}I\left[\frac{t - [t/\tau]\tau}{\tau} - \frac{1}{2}\right]\cos(\hat{\omega}(t - [t/\tau]\tau)) \qquad (2)$$

where $N = f_c\tau$ is the number of rf cycles between high-current bunches. The first term in equation (2) is the usual CW beam loading produced by the average current. The second term in equation (2) gives the voltage fluctuation from the fact that not every bucket is filled. The amplitude of the fluctuation is a saw-tooth function. It is found that the 120 pC, 7.5 MHz FEL bunches produce a voltage droop of $1.1 \cdot 10^{-4}$ at a gradient of 5 MV/m. In the frequency domain, there are sidebands with expansion coefficients

$$\Delta V_{\pm N \pm m} = -\frac{(R/Q)I}{4i}\left[\frac{N}{\pm m} + \frac{N}{\pm m \pm 2N}\right]$$

at frequencies $\pm f_c \pm m/\tau$. The voltage fluctuation can be partially corrected by having a set of cavities tuned to these sidebands. The cancelling of the first four sidebands decreases the induced rms energy spread by a factor of 5.

Since the FEL bunches will be accelerated off crest in the baseline scenario during simultaneous operation, good phase stability is essential. The basic phase control specification for the CEBAF RF system is at the 0.1 degree level and provides 10^{-4} stability for the nuclear physics and dedicated FEL bunches, which are accelerated on crest. This level of control would yield 10^{-3} stability for the FEL bunches at 25° off crest. Earlier tests [7] with beam in a relatively noisy laboratory environment exhibited the required phase control, and the RF system was well behaved when beam was accelerated off crest. More extensive testing is currently underway in the vibrationally quieter accelerator tunnel to fully characterize phase and amplitude control performance with heavy beam loading.

Wakefields

In addition to the average current (200 μA), good transverse and longitudinal beam quality is necessary for effective nuclear physics experimentation. The design goals are a full energy spread of 10^{-4} and an unnormalized emittance of $2 \cdot 10^{-9}$ m at 1 GeV and above. Such beam quality needs to be preserved when there is simultaneous FEL operation.

When the high-charge FEL bunches pass through the superconducting cavities, both the fundamental mode and higher order modes (HOMs) of the structure are excited. The higher-frequency modes are strongly damped within the interbunch spacing and produce wakefields that act effectively only within the bunches. These diffractive wakefields, however, produce much of the internal-bunch energy spreads. Both numerical calculations with TBCI [5] and analytic extrapolations [6] have been used to estimate the induced energy spread of the FEL bunches. Values at the 10^{-3} level have been obtained. Although most of the nuclear physics bunches are well outside the range of this short term wakefield, one class of bunches, those within the same RF cycle as the FEL bunches, is within 46 ps (25° of RF phase) of the highly charged FEL bunches. The distance involved, 1.4 cm, is of the order of the beampipe radius, and is in the transition region between short-term and long-term wakefield effects. For a typical cavity cell with transition steps, TBCI modeling shows that the wakefields at 46 ps are dominated by low frequency modes (long-term region), and it is estimated that that bunches nearest to the FEL bunches will experience an energy error of 10^{-4} in acceleration through the North and South Linacs. However, the value obtained is sensitive to uncertainties in the frequency content of the wakefield. On the other hand, the recirculation times are not synchronous with the FEL bunch repetition frequency, and this error will be proportionally reduced in multipass operation.

The fundamental and the lowest higher-order modes have relatively high Qs and can "ring" for times long compared to the bunch spacing. The excitation of the fundamental acts against the klystron-induced fields, and causes the 10^{-4} droop in the cavity voltage described in the previous section. In addition, it is estimated that the low-frequency, high-Q HOMs will induce a peak-to-peak 10^{-4} jitter. Since this occurs only in the North Linac (no FEL beam in the South Linac), the accumulated energy droop and jitter is halved, and pass-to-pass phase shifts between the nuclear physics and FEL bunches will further reduce the maximum fluctuations. Therefore, the energy variations induced by the FEL bunches on the nuclear physics bunches are expected to be well below the 10^{-4} design goal. Numerical modeling of the analogous transverse wakefield effects shows considerably smaller perturbations relative to performance goals.

References

[1] G. Neil, *et al.*, "FEL Design Using the CEBAF Linac," presented at Thirteenth International Free-Electron Laser Conference (1991).

[2] J. Bisognano, E. Gianfelice, and L. Palumbo, "Linac Collective Effects," in Conference Proceedings, volume 9, Italian Physical Society (1988).

[3] R. Sundelin, CEBAF Technical Performance Note, TPN 91-006 (1991).

[4] G. Krafft and S. Laubach, CEBAF Technical Note, TN-0153 (1989).

[5] T. Weiland, Nuclear Instr. Meth., 212, 13 (1983).

[6] S. Chattopadhyay, ed., Impedance Beyond Cutoff, Particle Accelerators, 25,2-4 (1990).

[7] S. Simrock, *et al.*, "Operation of the RF Controls in the CEBAF Injector," in Proceeding of Second European Particle Accelerator Conference (1990).

Figure Captions

Figure 1 IR FEL Bypass Transport System

Figure 2 Figure 2 UV FEL Bypass Transport System