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CONTINUOUS ELECTRON BEAM ACCELERATOR FACILITY

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STATUS REPORT ON THE CEBAF IR AND UV FELS*

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The CEBAF five pass recirculating, superconducting linac, being developed as a high power electron source for nuclear physics, is also an ideal FEL driver. The 45 MeV front end linac is presently operational with a CW (low peak current) nuclear physics gun and has met all CEBAF performance specifications including low emittance and energy spread \(< 1 \times 10^{-4}\). Progress will be reported in commissioning. This experience leads to predictions of excellent FEL performance. Initial designs reported last year have been advanced. Using the output of a high charge DC photoemission gun under development with a 6 cm period wiggler produces kilowatt output powers in the 3.6 to 17 \(\mu m\) range in the fundamental. Third harmonic operation extends IR performance down to 1.2 \(\mu m\). Beam at energies up to 400 MeV from the first full CEBAF linac will interact in a similar but longer wiggler to yield kilowatt UV light production at wavelengths as short as 0.15 \(\mu m\). Full power FEL operation can be accomplished simultaneously with high quality nuclear physics beam production. A FEL user facility has been designed for industrial research and technology development. Status of FEL-specific hardware will be reported.

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I. Introduction

The development of superconducting radiofrequency (SRF) cavities has reached a level that permits comprehensive designs of practical high power accelerators for FELs and other purposes. Designs based on this technology have a number of advantages including CW operation resulting in high average power, better beam stability, lower higher order mode (HOM) generation due to larger apertures, and potentially high wallplug efficiencies by incorporating energy recovery. In addition, the beam breakup limit of superconducting accelerators generally exceeds the required current by a significant margin so that the use of recirculation to reduce the required number of cavities is attractive.

These potential advantages need examination in light of present experience with large superconducting accelerators. The Continuous Electron Beam Accelerator Facility (CEBAF) [1] is a prime example of the progress that SRF technology has made. CEBAF was designed to operate at 1497 MHz due to the needs of nuclear physics users and the relative maturity of the Cornell superconducting cavity design on which it is based. CEBAF will be operational in 1994 and is designed for CW operation at an average current of 200 $\mu$A at a full energy of 4 GeV. The specified emittance ($< 2$ nm at 1 GeV) and energy spread ($< 10^{-4}$) are extremely tight although the design peak current is too low to give significant gain in an FEL. The 338 superconducting cavities have a specified gradient of 5 MeV/m and have a unique higher order mode load design to dissipate higher order modes (HOMs) in the 2.1 K helium bath. Each cavity is powered by its own 5 kW klystron.

The performance of the systems has been measured in a series of Front End tests. The CEBAF Front End operates at 45 MeV nominally but for this series of experiments a recirculation system was added to give the capability of operating at 85 MeV or in energy recovery mode back down to 5 MeV (see Figure 1). In 3000 hours of beam tests all electron beam specifications were met. No degradation of the operating gradient or reliability has been observed over this time. The emittance at 45 MeV was better than $2 \times 10^{-8}$ m in both planes and the longitudinal emittance was calculated to be less than $15\pi$ keV-degrees based on measured bunch length, bounded energy spread and verified upright phase ellipse. Up to 370 $\mu$A CW was accelerated at 45 MeV. Bunch lengths under 0.5° (0.9 ps)
were routinely obtained. The rf system has also performed beyond specification delivering amplitude stability of $1.5 \times 10^{-4}$ and phase stability better than 0.03°. As of August, 1992, 12 cryomodules were installed in the North Linac containing 96 superconducting cavities in addition to the 18 in the Front End for 285 MeV nominal energy. In initial testing the performance of these cavities has been superior with operating gradients averaging better than 8.5 MeV/m. Cavity Qs also exceed specification (see Figure 2). Electron beam testing of the Front End and North Linac began in mid-August. For multipass beam breakup, both analytical and numerical modeling predict a 14 mA threshold, based on bench measurements of higher-order modes (HOMs). In the 80 MeV recirculation experiment, with a predicted threshold of several mA, successful recirculation of 190 μA shows that HOM damping is sufficient. Modeling was also carried out to establish linac peak current limitations. Wakefields were estimated both numerically and analytically, and the studies included both cavities and vacuum chamber elements. The modeling shows a self-consistent parameter set of 300 A at 2 ps bunch length, with normalized emittance of 3 mm rr and energy spread of $5 \times 10^{-4}$ rms.

Using the output of a photoemission gun through the Front End with an electromagnetic, 6 cm period, 1.5 m long wiggler produces kilowatt output powers in the 3.6 to 17 μm range in the fundamental. Third harmonic operation extends IR performance down to 1.2 microns. Beam at energies of 400 MeV from the first full CEBAF linac will interact in a similar manner but calculations indicate that a 6 m long wiggler in an optical klystron configuration will yield kilowatt UV light production at wavelengths as short as 0.15 μm. Details of the design can be found in a previous publication.[2] A novel optical resonator design [3] is required to handle the UV power even using a 60 m long resonator. Design and construction of injector modifications are underway. The following section details these activities.

II. The FEL Injector

The FEL injector must provide a continuous train of 2-ps-duration bunches at a bunch repetition frequency of 7.485 MHz. Each bunch must contain a charge of 120 pC, corresponding to a 900 μA average current. The normalized rms emittance must be smaller
than 15 mm-mrad. Specifications for the FEL injector are summarized in Table 1.

The solution adopted to deliver this bunch train employs a high voltage DC electron gun with a photoemission cathode, followed by a room temperature prebuncher and a 10 MV/m CEBAF two-cavity cryounit (quarter-cryomodule) which both bunches and accelerates. See Figure 3. The photoemission gun with its associated laser system generates a 7.485 MHz train of low-emittance bunches containing sufficient charge, but with a 4σ pulse width of 100 ps. These long-duration but otherwise acceptable bunches are further bunched by the room temperature prebuncher, by the two superconducting cavities in the cryounit, and by the injection chicane to the desired microbunch length of \( \sim 2 \) ps before the first eight-cavity cryomodule of the standard CEBAF nuclear physics injector.

The FEL injector is located in the drift region between the cryounit and the first cryomodule of the present CEBAF nuclear physics injector. A first-order achromatic isochronous beamline has been designed to transport the 5 MeV nuclear physics beam around the FEL injector. This 5 MeV beam is combined with the 10 MeV FEL beam at the entrance of the first eight-cavity injector cryomodule. This bypass is shown in Figure 3, and its transport functions are shown in Figure 4.

Bunching and Pre-Acceleration System

Following the 500 kV photocathode gun, the beam enters a two-cell fundamental frequency room temperature prebuncher operated with a field gradient of 1.3 MV/m. This buncher is very similar to two cells of the five-cell capture section used in the present accelerator injector. Consequently, the rf power system, the phase and amplitude controls, and the temperature control for this cavity will closely follow those developed for the capture section.[6]

In the two-cavity cryounit that follows the prebuncher, both cavities are operated somewhat off crest, so that these cavities both bunch and accelerate. Both cavities are operated at a gradient of 10 MV/m, which, though higher than the nominal operating gradient for CEBAF cavities, is equal to the average gradient routinely achieved with present production techniques.[7] As with the prebuncher, the CEBAF rf control system
[6] will be used with these cavities. The beam energy after the cryounit is about 10 MeV. Bunches are 4 ps long at the exit of the cryounit. More bunching is provided by the combination chicane, which has a transport $M_{48}$ of $\sim -0.1$ m. The bunches reach their shortest length of 2 ps at the end of the chicane, just before the entrance of the first injector cryomodule.

The transverse optics for the FEL injector are particularly simple. A pair of solenoidal lenses, one between the gun and the prebuncher and one surrounding the prebuncher, are used in the 500 keV beamline between the photoemission gun and the cryounit. A triplet of quadrupoles after the cryounit is used to counter the vertical focusing effects due to the edges of the chicane dipoles, and to focus the 10 MeV beam as it enters the first full injector cryomodule.

The code PARMELA [8] was used to optimize the beam dynamics of this injector design. We computed the dynamics of an initial charge of 160 pC, with a 3 mm beam radius, 10 mm-mrad transverse rms normalized emittance, 100 ps (4$\sigma$) pulse length and 14 keV-degrees longitudinal emittance at the gun anode. The simulations show that the transverse focusing in the proposed scheme is sufficient to keep the beam confined within a 1.4 cm radius, with little phase-space dilution from space charge. Figure 5 shows the resulting longitudinal phase space at the injector and the corresponding phase and energy spectra. The computation of the beam core dynamics shows a 60 A average current (120 pC) within 2 ps (1.1$^\circ$) of bunch length and a total energy spread smaller than $2 \times 10^{-3}$.

**Photocathode Gun and Laser System**

The electron beam will be produced by photoemission from a 3-mm-diameter photocathode.[9] The peak current density is below 20 A/cm$^2$, which requires only a modest field strength at the cathode surface. The gun (Figure 6) will be operated at 500 kV, and have an anode-cathode gap greater than 10 cm. A flat anode and cathode will be used, rather than the more conventional Pierce geometry, to avoid temporal degradation of the electron pulse. As the 100 ps pulses are “long,” high-quantum-efficiency GaAs photocathodes will be used. The code POISSON [10] has been used to determine electrode shapes which maintain a uniform cathode field over the active cathode area, and which
limit the maximum field strength on the cathode electrode to an acceptable level. The code EGUN has been used to verify the DC performance of the gun design, and the code PARMELA (with a modification due to McDonald [11]) has been used to verify the transverse emittance and pulse duration for the 100 ps pulse case.

The laser requirements for the photoemission gun can be readily met with straightforward modifications to commercially available equipment. Optical pulses at 527 nm from a frequency-doubled, actively mode-locked CW Nd:YLF laser are well suited to our requirements. At 527 nm, a 1% quantum efficiency photocathode provides 4.25 mA of electron beam per watt of optical power. As typical GaAs photocathodes have quantum efficiencies well above 1%, a design based upon 1/2% quantum efficiency is quite conservative. This requires a laser with peak optical power below 1 kW, and an average power of less than 1/2 W.

These developments are currently underway. The high gradient cryomodule has been fabricated, tested and meets all specifications. The laser system is presently in procurement. Engineering drawings of the gun now exist and the gun is in fabrication.

III. Operational Transparency

One unique aspect of the FEL design is that full power FEL operation can be accomplished simultaneously with delivery of a high quality nuclear physics beam. The following section summarizes the analyses used to verify the operational transparency of the two systems.

Simultaneous FEL and Nuclear Physics Operation

Electron beams of quite distinct character must be provided for the nuclear physics end stations and the FEL wigglers. FEL operation requires electron bunches carrying charges of 120 pC at a repetition rate of 7.5 MHz, whereas the nuclear physics experimenters demand relatively low charge per bunch, much less than 1 pC, but at a repetition rate of approximately 1.5 GHz. Consequently, the coordinated production and delivery of these two dissimilar particle beams must be carefully planned. The early stages of FEL experimentation will not directly conflict with nuclear physics experiments, which will be
coming on-line during 1994, but FEL operation will need to share time with the primary effort of accelerator commissioning. Once full nuclear physics operation begins, however, coordination between the two programs becomes critical, and, since the principal mission of CEBAF is nuclear physics, FEL research activities must interfere only minimally with this effort. Although dedicated FEL operation for a modest fraction of beam time may be quite workable, especially during the incipient stages of nuclear physics operations, a more transparent mode is desirable to take full advantage of the FEL hardware and to allow for maximum flexibility for all users. Such a mode ideally would accelerate and deliver the two disparate beams simultaneously with negligible degradation of beam quality.

Options for simultaneous FEL and nuclear physics beams are constrained by installed rf power, induced wakefields, and beam transport complexity. Together, these issues provide a fairly well defined set of design choices. In this section the rationale for the parameter sets selected is given.

**rf Power**

Each CEBAF superconducting cavity is driven by a klystron-based rf system with a nominal saturated power of 5 kW. A minimum output power of 4 kW is specified with sufficient marginal loop gain to provide the $10^{-4}$ energy control required for the nuclear physics program. It is expected that during much of the nuclear physics running time considerably less than the design maximum average current of 200 $\mu$A will be requested; for example certain classes of experiments cannot tolerate the full beam current. For this proposal, a baseline nuclear physics current of 100 $\mu$A is assumed. With 4 kW/cavity available rf power, this assumption implies that 900 $\mu$A can be accelerated for FEL activities. At a repetition frequency of 7.5 MHz, each FEL bunch will contain 120 pC. Modest upgrades to the klystron power supplies would provide sufficient power to accelerate the design-maximum 200 $\mu$A for the nuclear physics end stations concurrently with the baseline 900 $\mu$A for FEL operations.

**Wakefields**

In addition to high average current, 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. These issues were successfully treated in a previous paper; see [12].

**Beam Transport**

The FEL electron beam from the CEBAF injection linac must be separated from the nuclear physics beam and transported into the wiggler inside the IR FEL optical cavity with appropriate optical matching. To match the wiggler focusing strength, the $\sim 50$ MeV FEL beam must be focused to a 0.3 mm radius spot at the wiggler. With a normalized beam emittance of 15 mm-mrad, this implies fairly strong focusing to $\beta^* \approx 1.0$ m at the wiggler. Small or zero dispersion is also needed.

The transport begins after the injection linac accelerating cryomodules, where the nuclear physics beam is at 45 MeV, and the FEL beam from the 10 MeV injector is at the higher energy of 50 MeV. A bending magnet displaces both beams from a linear transport, with the FEL beam bent at $11.5^\circ$. At 1.2 m downstream, where the beams are separated by 2.5 cm, the FEL beam enters a septum dipole which bends the FEL beam back by $-23^\circ$ to the opposite side of the injector line. A 4 m transport containing three quads for dispersion correction carries the FEL beam to a third dipole where the beam is bent $11.5^\circ$ toward the wiggler. A 3.5 m transport containing four quads matches the beam into the wiggler. The matching conditions chosen in this example are $\beta_x^* = \beta_y^* = 1.0$ m at the wiggler center. Figure 7 shows beam transport accommodates a 20 m optical cavity centered on the wiggler. Fine tuning of the vertical focusing can provide matching to the wiggler focusing (matched $\beta_y^* = 0.5$ m with $K = 1.76$). At these parameters the electron beam is much smaller than the optical beam. Therefore, the focusing could be significantly relaxed without degrading FEL gain; FEL performance will not require precise electron beam optics.

The wiggler would be followed by a bending magnet and a couple of focusing quads which guide the FEL beam into a beam dump. The beam dump is designed to accept the 60 kW output of a full-intensity IR FEL beam.

The nuclear physics beam continues outside the septum to reach a separate dipole,
which returns the nuclear physics beam to the injector line to continue toward the North Linac. The resulting dogleg does not greatly affect the nuclear physics betatron functions, but does introduce an $M_{58}$ of $\sim -0.2$ m, which can be compensated in the North Linac injection chicane.

The UV FEL beam transport must accommodate three functions: it must separate the FEL bunches from the nuclear physics bunch trains, it must provide longitudinal compression of the FEL bunch, and it must provide a phase-space match into the wiggler. The entire system must fit within the North Linac tunnel.

To permit energy separation of the FEL beam from the nuclear physics beams, the FEL bunches are phased 25° off the crest of the rf wave, generating a 10% energy offset. The FEL beam is at 400 MeV at the end of the North Linac, with the first-turn nuclear physics beam at 445 MeV. This difference is used to separate the beams, while the off-crest operation places an energy tilt in the FEL bunches which is used to obtain compression. The beam transport must also match the beam to the optical mode within the wiggler (2σ spot size of 300 μm, which implies $\beta^* \approx 1$ m), with adequate momentum acceptance ($\sim \pm 0.005$).

The relatively stringent transport specifications have led to a modular, achromatic, and nominally isochronous beamline design. A cross-sectional view of the tunnel at the wiggler is shown in Figure 8. The FEL beam is separated from all nuclear physics beams by the common dipole at the front end of the east arc spreader. Beam transport elements produce vertical, then horizontal, translations away from the linac axis, followed by modules for bunch compression and matching into the wiggler. We now describe each of these systems in order.

From the 10% energy offset, the FEL beam will be vertically offset from the nuclear physics beam by over 10 cm at the first independent dipole of the lowest-energy recirculation arc. This is adequate for the introduction of a quadrupole doublet to control the betatron envelopes of the 400 MeV FEL beam. After the quadrupole doublet, the FEL beam is bent onto a trajectory parallel to the linac axis, vertically displaced by 2 m. At this point, the beam is directed towards the lowest-energy east arc, is vertically dispersed
with zero dispersion slope, and has a negative path-length variation with momentum. To avoid the east arc while remaining in the tunnel, a horizontal translation away from the linac axis is required. This translation introduces a horizontal dispersion. To avoid the complication of two-dimensional dispersion matching and to correct simultaneously the path-length dependence on momentum, a phase-space rotator is introduced to transform the (negative) vertical dispersion at the end of the vertical translation into a (positive) horizontal dispersion at the beginning of the required horizontal translation. The horizontal translation is generated using a dipole geometry identical to that of the vertical, and a quadrupole triplet is introduced for dispersion suppression; the resulting combined horizontal/vertical translation is achromatic and nearly isochronous.

The phase-space rotator consists of a single quadrupole followed by a solenoid. The quadrupole and the solenoid transform the vertical angular divergence into a horizontal dispersion with zero slope. The required solenoid strength is given by the following condition:

\[ \int Bdl = \pi (B\rho) \]

For a 400 MeV beam, this requires a field integral of 42 kG-m. We use a relatively long solenoid of 4 m, with a moderately long focal length \((B/(2B\rho))^{-1}\) of about 2.5 m. (Other phase-space rotators based on skew quadrupoles have been designed but are operationally more complex and appear less cost-effective.)

Immediately following the horizontal translation, a quadrupole doublet is introduced for the purpose of controlling beam envelopes in both transverse planes. After this matching doublet, a bunch compression module based on a symmetric two-doublet insertion with an embedded horizontal three-dipole chicane provides an achromatic variation of path length with momentum without modification of incident or extracted betatron functions. By modifying the excitation of the chicane, a range of \(-1 \text{ m} \leq M_{66} \leq 0 \text{ m}\) can be produced. This is adequate to generate the desired bunch compression.

A betatron telescope consisting of a pair of quad doublets then provides matching to the wiggler across a final dispersion-suppressed vertical transverse translation. This final
translation onto the axis of the wiggler and optical cavity is a 0.5 m offset provided to ensure the optical beam clears all beam transport equipment. The final matching telescope can be tuned to provide a range of matching conditions. We have investigated the cases of upright ellipses with either $\beta^{wiggler} = 1$ m or $\beta^{wiggler} = 4$ m in both transverse planes at the center of a 3 m, 50 period wiggler. Figure 9a presents rms beam spot sizes though the system for a quasi-isochronous (no compression) case with the anticipated initial emittances of $2 \times 10^{-8}$ m-rad in either plane, and a final match to upright ellipses with $\beta^{wiggler} = 1$ m at the center of the wiggler, in both planes. Dispersions are shown in Figure 9b.

Following the wiggler, spent beam is transported to a beam dump in the North Linac tunnel stub.

IV. Conclusion

A realizable design for the transport systems to the IR and UV FEL has been achieved. Component requirements have been identified and all transport elements designs can be easily achieved. Development of this hardware is proceeding at a pace consistent with CEBAF’s prime mission and the availability of funds. A FEL user facility has been designed for industrial research and technology development and industry has offered $9M of in-kind contributions to support technology development at this facility. The Commonwealth of Virginia has also pledged $5M in matching funds and a proposal to DOE is pending.
Table 1
FEL Injector Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>10 MeV</td>
</tr>
<tr>
<td>Microbunch repetition rate</td>
<td>7.485 MHz</td>
</tr>
<tr>
<td>Charge per microbunch</td>
<td>120 pC</td>
</tr>
<tr>
<td>Average beam current</td>
<td>900 µA</td>
</tr>
<tr>
<td>Bunch length (4σ)</td>
<td>2 ps</td>
</tr>
<tr>
<td>Normalized emittance (εₙ)ᵃ</td>
<td>&lt; 15 mm-mrad</td>
</tr>
<tr>
<td>Longitudinal emittance</td>
<td>50 keV-degrees</td>
</tr>
</tbody>
</table>

ᵃ) $\sigma_z = \sqrt{\beta_z \varepsilon_n / \gamma}$
Figure Captions

Figure 1 The CEBAF Front End with the recirculation system installed.

Figure 2 Recent performance of the CEBAF cavities. The gradient quoted is the actual operating gradient. No field reduction is required with beam operation.

Figure 3 FEL injector and nuclear physics beam bypass (dimensions in cm).

Figure 4 Beam transport functions \( (\beta_x, \beta_y, \eta_x) \) from the exit of the CEBAF injector cryounit to the first cryomodule entrance are shown. They are calculated using DIMAD [4] with parameters from a PARMELA [5] simulation as input.

Figure 5 Macroparticle distributions from a PARMELA simulation of the FEL injector followed by the two cryomodules \( (E_e = 10 \text{ MeV}) \). Upper left: distribution in longitudinal phase \( (\phi, \Delta E) \). Upper right: density projection in energy \( (\Delta E) \), showing energy spread. Lower left: density in longitudinal phase \( \phi \), showing phase spread; the 2 ps beam width is indicated.

Figure 6 Cutaway view of 500 kV gun structure. In operation, the HV sections will have corona protection and be in a SF\(_6\) tank.

Figure 7 Plot of the beam transport functions \( (\beta_x, \beta_y, \eta) \) for the IR FEL. The 1.5 m IR wiggler is at the end of the transport line.

Figure 8 Cross-sectional view of the CEBAF accelerator tunnel in the east arc spreader region showing the location of the UV wiggler.

Figure 9a Horizontal and vertical rms spot sizes \( (\sigma \text{ matrix elements } \sigma_x \text{ and } \sigma_y) \) through transport system, from linac to wiggler center. Uncoupled unnormalized initial emittances \( \epsilon_x = \epsilon_y = 2 \times 10^{-8} \text{ m-rad} \) were assumed, the initial phase ellipses were assumed upright with \( \beta_x = 5 \text{ m} \) and \( \beta_y = 50 \text{ m} \), and the final match is to upright phase ellipses with \( \beta_{x,\text{wiggler}} = \beta_{y,\text{wiggler}} = 1 \text{ m} \) at the center of the 3 m, 50 period wiggler. Solid lines indicate
the horizontal, and dashed lines the vertical, spot size; bold lines indicate beam size with \( \sigma_{\delta p/p} = 0 \) (dispersive effects neglected); light lines indicate beam size with the anticipated \( \sigma_{\delta p/p} = 2 \times 10^{-3} \).

**Figure 9b** Horizontal and vertical dispersions through transport system, from linac to wiggler center. Transport and matching conditions are as before; solid lines represent horizontal, and dashed vertical, dispersion.
References:


RMS Beam Sizes $\sigma_x$, $\sigma_y$ (m) for $\sigma_{\delta p/p} = 0$, $2 \times 10^{-3}$
Dispersions $\eta_x, \eta_y$ (m) Through System