DESIGN OF THE SRF DRIVER ERL FOR THE JEFFERSON LAB UV FEL*

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Abstract

We describe the design of the SRF Energy-Recovering Linac (ERL) providing the CW electron drive beam at the Jefferson Lab UV FEL. Based on the same 135 MeV linear accelerator as – and sharing portions of the recirculator with – the Jefferson Lab 10 kW IR Upgrade FEL, the UV driver ERL uses a novel bypass geometry to provide transverse phase space control, bunch length compression, and nonlinear aberration compensation (including correction of RF curvature effects) without the use of magnetic chicanes or harmonic RF. Stringent phase space requirements at the wiggler, low beam energy, high beam current, and use of a pre-existing facility and legacy hardware subject the design to numerous constraints. These are imposed not only by the need for both transverse and longitudinal phase space management, but also by the potential impact of collective phenomena (space charge, wakefields, beam break-up (BBU), and coherent synchrotron radiation (CSR)), and by interactions between the FEL and the accelerator RF system. This report addresses these issues and presents the accelerator design solution that is now in operation [1].

DESIGN REQUIREMENTS

The JLab UV Driver ERL design must meet multiple requirements imposed from disparate sources. It must, firstly, accomplish two fundamental tasks: deliver to the wiggler an electron beam with phase space appropriately configured to drive the FEL interaction, and energy recover the large-energy-spread exhaust beam from the FEL. These activities must be completed in a manner observant of three ancillary constraints imposed by dynamical processes associated with high brightness, high power CW beams: preservation of beam quality, avoidance of instabilities and management of beam loss. In addition, installation in a facility sharing infrastructure with the legacy IR Upgrade FEL [2] imposes constraints on the geometry of the beam line and motivates sharing and reuse of IR Upgrade hardware whenever possible.

The first task demands the capability of transverse and longitudinal phase space matching during transport to the wiggler and during the energy recovery cycle. The beam size and divergence must be set to assure overlap with the optical mode in the FEL, and the bunch length compressed to provide the high peak current required for lasing. Beam quality must be preserved in the presence of space charge, wakefields, environmental impedances, and CSR. Beam sizes must be modest and the large FEL exhaust energy spread compressed to avoid beam loss in the linac as the beam power is recovered. Collective effects such as BBU and the FEL/RF interaction must be managed, and beam loss carefully controlled.

Legacy facility features further constrain the design. In particular, the elevation of the available wiggler (1.4 m) demands use of a laterally offset beam to employ a pre-existing "wiggler pit" that lowers the wiggler midplane to the JLab-standard beamline elevation of 0.7 m.

DESIGN CONCEPT

The design described here meets these requirements by retaining, insofar as is possible, solutions employed in the IR upgrade. We use the same modular approach, and similar – or in some cases common – optics modules in both systems. The overall configuration is shown in Figure 1 (with the IR Upgrade-specific transport shaded). Beam is switched between the IR and UV transport by modifying the excitation of the final (first) main dipole of the delivery (recovery) recirculation arc by use of a multi-segment coil pack [3]. This allows diversion of the beam to the UV FEL with minimal operational modification.

Figure 1: System layout in vault: IR Upgrade transport gray-shaded; GX/GW transport dipoles as indicated.

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The acceleration and delivery transport comprise a 9 MeV injector [4], a three-cryomodule (each with eight 1.497 GHz SRF cavities) SRF linac, a 6-quadrupole telescope matching the linac to a Bates-style recirculation arc, four periods of FODO transport providing dispersion and beam envelope control, a final bend onto the FEL axis, and a 6-quadrupole telescope matching beam envelopes from the recirculation arc to the wiggler, which resides in a pit used to lower the magnetic mid-plane to nominal accelerator elevation. The recovery transport is a mirror image of the delivery, with a sequence of modules managing both transverse and longitudinal phase space to avoid beam loss, compress energy spread during recovery, and control collective effects and instabilities. Table 1 presents system parameters achieved in the IR Upgrade FEL and design values for the UV Driver ERL.

Table 1: System Parameters

Parameter	IR	UV
Energy (MeV)	88-165	80-210
I_{ave} (mA)	9.1	5
Q_{bunch} (pC)	135	60
$\epsilon_N^{transverse}$ (mm-mrad) $\epsilon_N^{longitudinal}$ (keV-psec)	8 75	5 50
$\sigma_{\delta p/p}$, σ_l (fsec) (wiggler)	0.4%, 160	0.3-0.4%, 133-100
I_{peak} (A)	400	250
FEL rep. rate (MHz)	0.58-74.85	4.678-74.85
(32 m optical cavity fundamental = 4.678 MHz)		
η_{FEL}	2.5%	0.8%
ΔE_{full} after FEL	~15%	~7%

BEAM TRANSPORT SOLUTION

The design leverages substantial amounts of IR Upgrade hardware, infrastructure, and experience [5]. UV-specific features include the following.

System Geometry

The UV ERL layout is constrained by the vault, which was designed to house a legacy design [6]. Subsequent installation and operation of the IR Upgrade provided an installed (but quite different) hardware base that could, through appropriate modification, be largely utilized to recirculate beam while still delivering it to a wiggler located in a pit – an approach intended to allow use of storage ring standard elevation (1.4 m) in a machine with CEBAF-nominal beam elevation (0.7 m). As a consequence, the UV ERL transport is displaced from that of the IR ERL, and is therefore configured as a "bypass". Both systems employ a common SRF linac and use the same recirculation arcs. The bypass is realized by reducing fields in the corner "GX" dipoles at the ends of the Bates arcs in the IR transport so as to direct beam toward the wiggler; the bend onto the wiggler axis is then completed using a standard rectangular "GW" dipole from IR inventory [7] (Figure 1). The bend angles are defined by the residual angle provided when the GX core field is set to half of the nominal IR value [8]; the effective length of GW was chosen to complete the bend. The length of the backleg transport – from end to end – is set so that the 32 m UV optical cavity lies outside the electron beam transport, thereby (unlike the IR transport) avoiding use of any chicanes around optical cavity mirrors.

Injector

The IR Upgrade injector is optimized for operation at a bunch charge of 135 pC and thus delivers ~10 mA at 74.85 MHz (limited by the drive laser fundamental). To produce the smaller emittance required at shorter UV FEL wavelengths, the injector was reoptimized (by reduction of front-end solenoid and RF buncher excitations, rephasing of cavities, and rematching of envelopes from injector to linac using the injector matching telescope) to operate at a single-bunch charge of 60 pC. The lower charge gives small emittances, though at the cost of lower average current (5 mA at 74.85 MHz).

Longitudinal Matching

The UV ERL utilizes a single-stage bunch length compression scheme [9] similar to that employed in the IR Upgrade [10]. A long, low-momentum-spread injected bunch is chirped by off-crest acceleration on the rising portion of the linac RF waveform; the resulting phase-energy correlation insures that the bunch length is then compressed using the first and second order momentum compactions of the Bates arc. No use is made of harmonic RF or chicane compressors. This is in contrast to the IR Upgrade, where final compression is performed in the chicane transporting the electron beam around the upstream end of the FEL optical cavity. The match provides energy compression during energy recovery by using the inverse process: the short, large-energy spread exhaust bunch from the FEL is decompressed in length and differentially phase-matched to RF waveform using the momentum compactions of the recovery arc transport; the phase energy correlation at reinjection is controlled through third order using path length correctors, quadrupoles, sextupoles, and octupoles. This scheme can provide 250 A peak current at the wiggler and compress ~10 MeV full exhaust energy spread spread from the FEL to ~½ MeV full spread at the dump. The process is tunable over a broad range; the compactions are, order by order, orthogonally variable and the bunch aspect ratio can be adjusted by choice of RF phase operating point.

Transverse Matching

A sequence of five quadrupole telescopes match injector to linac, linac to recirculator, recirculator to FEL, FEL to recovery arc, and recovery arc to linac. Dispersion generated by the incomplete final bend (GX) out of the delivery Bates arc is managed by imaging the residual dispersive angle onto the GW dipole that bends the beam onto the FEL axis. This is done by using four periods of FODO transport to provide a full betatron wavelength in the bend plane, and a half-wavelength vertically; the choice of vertical phase advance is driven by the need to limit betatron mismatch and manage chromatic aberrations. The process is reversed in the recovery arc; Figure 2 presents betatron functions and dispersion through the system.

BEAM DYNAMICAL ISSUES

The UV design must address specific issues that differ in character or degree from the concerns associated with the earlier IR system. These are as follows.

Aberration Management

Aberration control is provided by keeping beam envelopes and quadrupole strengths as small as possible, and by care in choice of phase advances across matching telescopes (to produce destructive interferences amongst chromatic aberrations). Sixteen sextupoles in seven families control nonlinear dispersion and set T_{566} to offset RF curvature. Two provide independent adjustment of T_{566} in the delivery and recovery arcs; the others control nonlinear dispersion and are optimized to limit chromatic variation of lattice functions and geometric effects.

CSR

Design and operational experience with the IR system indicates that beam quality will be well preserved at UV bunch charges, despite parasitic compressions in the Bates arc [11,12]. Dispersion management in the bypass adds a parasitic compression, as the bunch is short in the GX switching magnet. The net angle over which the CSR force is large is thus approximately twice that in the IR system. As the charge is however only half of that in the IR, the integrated CSR force is notionally the same. Moreover, the final compression in the UV is at a point of very high dispersion, taking large portions of charge out of communication with itself, further reducing the net effect. The bending of the fully compressed bunch also occurs at locations with small dispersion and lattice functions, reducing the downstream response of the beam.

Mirror loading is an ongoing issue, but can in principle be mitigated as in the IR Upgrade [13] by use of a THz management chicane [14] (installed in a slot available downstream of the wiggler) and THz traps.

BBU

BBU effects have been characterized in detail in the IR ERL [15]; as the UV system shares a common linac transport, appropriate choice of phase advance can recover the same behavior. Unlike the IR system, the UV transport does not include a phase-space exchange (skew quad rotator). The lower beam current was judged to preclude any need for this; however, there is space available (in the arc-to-wiggler matching telescope) to retrofit such an exchange should it prove necessary.

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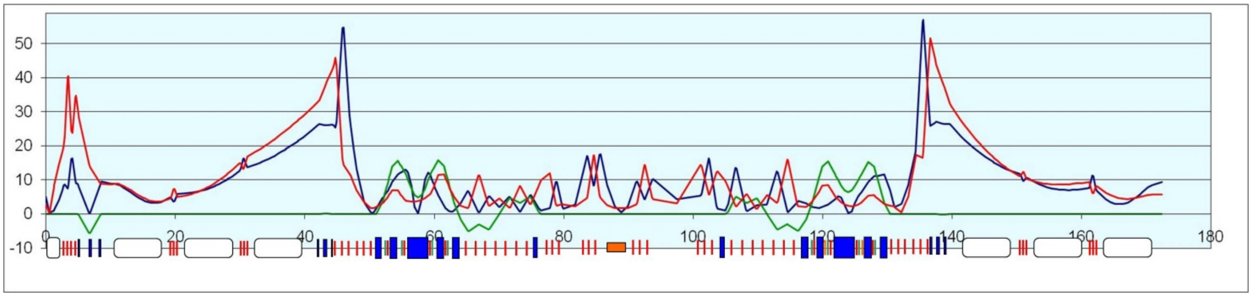

Figure 2: Betatron functions and dispersions (β_x, blue; β_y, red; $10*\eta_x$, green; all in meters)