DESIGN CONCEPT FOR A COMPACT ERL TO DRIVE A VUV/SOFT X-RAY FEL*

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Abstract

We explore possible upgrades of the existing Jefferson Laboratory IR/UV FEL driver to higher electron beam energy and shorter wavelength through use of multipass recirculation to drive an amplifier FEL. The system would require beam energy at the wiggler of 600 MeV with 1 mA of average current. The system must generate a high brightness beam, configure it appropriately, and preserve beam quality through the acceleration cycle – including multiple recirculations – and appropriately manage the phase space during energy recovery. The paper will discuss preliminary design analysis of the longitudinal match, space charge effects in the linac, and recirculator design issues, including the potential for the microbunching instability. A design concept for the low energy recirculator and an emittance preserving lattice solution will be presented.

INTRODUCTION

With the recent success of generating 10 eV photons at the IR/UV FEL Upgrade at Jefferson Laboratory [1], we explore upgrade options that will enable us to push the photon energy to 100 eV. The proposed machine – henceforth referred to as JLAMP (Jefferson Laboratory AMPlifier) – is based on an energy upgrade to the existing energy recovering linear accelerator and takes advantage of multiple recirculations to generate beam energies in excess of 600 MeV at repetition rates up to 4.68 MHz with continuous wave RF [2]. The beam is injected into a linac comprised of 3 cryomodules, each capable of generating up to 120 MV. The beam is recirculated in a low energy arc, makes a second accelerating pass through the linac, and then is transported to the soft x-ray wiggler installed in a high energy recirculator. Following the wiggler, the beam is sent through the linac (3rd pass) for deceleration, traverses the low energy recirculator a second time and passes through the linac (4th pass) where the beam is decelerated to the injection energy and sent to a dump.

ELECTRON SOURCE AND INJECTOR

In order to realize the designed FEL performance, the electron beam must have a bunch charge of 200 pC and a normalized transverse emittance of less than 1 mm-mrad while operating at 4.68 MHz. At present, there is no definitive method of producing such a bright, CW beam and this poses a challenge for the electron source and injector. The three differing gun technologies (normal conducting, DC, superconducting) are all being evaluated to discern which can reliably meet the injector requirements. Following the gun, the relatively long bunch is velocity bunched using a buncher, then raised in energy (before space charge can degrade beam quality) using a booster. Studies focus on use of single-cell 750 MHz booster cavities; these capture the low energy beam without distorting the longitudinal phase space, and accelerate it to 10 MeV.

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LONGITUDINAL MATCH

JLAMP requires a longitudinal match wherein the bunch remains long through as much of the machine as possible (to reduce any ill effects from coherent synchrotron radiation (CSR) in the recirculation arcs) and then compressed rapidly at the wiggler. Furthermore, during energy recovery the system must be able to energy compress the exhaust beam from the FEL. To this end JLAMP will utilize the same longitudinal gymnastics that were successfully demonstrated in the IR Demo and the IR/UV Upgrade [3]; inject a long, low momentum spread bunch to mitigate space charge and accelerate off-crest to impose a phase-energy correlation which coupled with the proper compaction of the recirulator *fully rotates* the beam upright at the wiggler. Thus, the injected bunch length (energy spread) transforms to the energy spread (bunch length) at the wiggler. The momentum compaction of the wiggler-to-linac transport (including nonlinearities) is used to induce a phase-energy correlation matching the exhaust bunch energy distribution to the RF waveform, generating energy compression during deceleration. An initial design for the longitudinal match has been generated which delivers a distribution with a bunch length of 56 fs (rms) and 0.16% relative energy spread (rms) [4].

BEAM QUALITY PRESERVATION DURING ACCELERATION

PARMELA modeling of the first pass through the linac as a function of injected transverse match provides information on emittance growth in the presence of space charge forces. Figure 1 shows the transverse emittance growth (from an injected 1 mm-mrad distribution) at the exit of the first cryomodule as a function of the injected beta ($\beta_x=\beta_y$) and alpha ($\alpha_x=\alpha_y$). In addition to meeting the stringent emittance budget, we also look for well behaved beam envelopes (i.e. the beam envelopes do not become excessively large within the first 10 m of the linac). Large beam envelopes are more sensitive to focusing and steering errors, increases the likelihood of beam loss/scraping, requires strong focusing to match into the first recirculation arc with subsequent problems with chromatic aberrations and also increases the beam breakup (BBU) threshold current (by generating large turn-to-turn $M_{12,34}$ values). The plot shows that there are a range of injected values that puts us in a regime where the emittance growth is modest (5%) while still keeping the beam envelopes through the first module manageable [5].

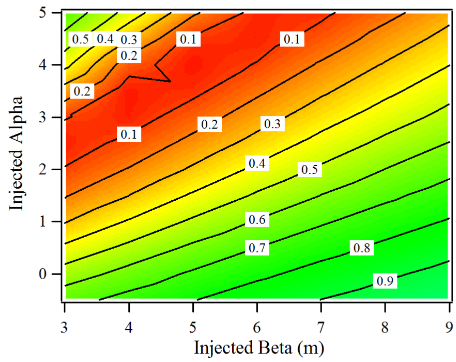

Figure 1: Emittance growth after the first cryomodule (110 MeV) as a function of injected transverse match.

LOW-ENERGY RECIRCULATOR

We consider in some detail the design of the low energy recirculator, as it will serve as an existence proof for a transport system providing adequate preservation of beam quality during recirculation [6]. The design is constrained by a number of items, not the least of which is that the system must fit in the existing FEL vault (roughly 12 m × 65 m). Additionally, chromatic and geometric aberrations must be controlled and the transport momentum acceptance must be adequate to support energy compression and recovery of the FEL exhaust beam. We take a modular approach to the design of the recirculator and each is detailed below. Figure 2 shows the recirculator design in the present FEL vault.

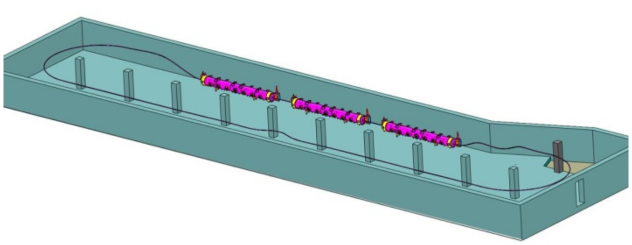

Figure 2: Plan view of the recirculator in the present FEL vault (courtesy J. Gubeli).

Spreader-Match

Separating the beams vertically for recirculation makes the best use of the available (limited) space in the vault. The spreader must bring the beam to an elevation of 1.4 m from the linac axis (2.1 m from the vault floor). We implement a single step (20° bends at 300 MeV) with seven quadrupoles in the vertical translation. The quadrupoles contain embedded sextupole terms to control nonlinear vertical dispersion (T_{366} and T_{466}). Following the second dipole two quadrupole triplets are used to transversely match the beam to the recirculation arc.

First Arc

Following separation of the various passes, we recirculate the beam using a 180° bending arc comprised of several periods of FODO (quadrupole-dipole-quadrupole) cells. This will make the arc footprint nearly circular (giving the most efficient utilization of available space), will provide periodicity and symmetry for aberration management and tuning capability and will decompress the bunch length and thereby alleviate CSR effects.

We find that adequate performance is provided by using twelve dipole-quadrupole-dipole cells tuned (using the quadrupole strength as a single family and the field index in the dipoles) to give 1/6th integer phase advance in the bending plane and 1/4th integer phase advance in the non-bending plane. With this choice, the arc is a second-order achromat, coupling error effects are suppressed (because of the split tunes), and the system momentum compactions can be tuned using periodically spaced “sub-families” of the quadrupoles. Specifically, the second, fifth, eighth, and eleventh quadrupoles are separated by 180° in betatron phase in the bending plane and 270° in the non-bending plane. They therefore can be used to perform a one-knob dispersion bump and modify M_{56} while keeping the arc achromatic; the quarter-integer separation in the non-bend plane serves to suppress perturbation of the out-of-plane betatron match. The specific choice of sixth integer horizontal phase advance ensures this bump occurs across three dipoles (rather than two as would occur for a quarter integer tune), providing potentially greater dynamic tuning range. Sextupoles at these locations can be similarly used to adjust T_{566}; similar multipoles at the locations of other focusing elements serve to manage linear and nonlinear dispersion. The use of twelve cells over a roughly 6 m radius transport ensures that the matched Twiss parameters and dispersions are small. This alleviates aberrations and error sensitivity, reduces response to CSR, and keeps the beam size relatively small – even during recovery of a potentially large energy spread beam.

Backleg

We choose a quadrupole FODO array with the phase advance chosen to assist in aberration suppression. The backleg is symmetric about the midpoint of the path length adjustment chicane. Following the arc a six quadrupole telescope transversely matches the beam into four 90° FODO cells. A short matching section matches the beam to the four-dipole chicane which is comprised of 24° bends (at 300 MeV) and is very similar to the layout of the optical cavity chicane in the IR/UV Upgrade. The chicane provides tunable path length adjustment over a full RF wavelength (0.2 m). Note that to maintain the isochronicity of the recirculator, any path length change in the chicane must be accompanied by a modification of the arc compactions to compensate for the change in the R_{56}.

Second Arc

The second arc is identical to the first arc.

Recombiner-Match

We use a clone of the CEBAF staircase, with a six quadrupole matching telescope followed by a vertical half-chicane (25° bends at 300 MeV). Five quadrupoles are used for beam envelope control with embedded sextupoles to manage nonlinear vertical dispersion. A second half-chicane delivers the matched and recompressed beam to the linac axis. The "double half chicane" structure has a large negative R_{56} and thus compensates for the naturally positive arc compaction. By tuning the arc compactions (using quadrupole and sextupole terms) one can adjust the overall recirculator compaction schedule to achieve a range of longitudinal matches.

System Performance

Figure 3 shows the beta functions for the baseline design of the low energy recirculator. Analysis of chromatic aberrations for the recirculator has been performed and suggests that aberration management is adequate. Momentum scans indicate that beam quality of the accelerated beam will be well maintained (as parameters are flat over ±2% moment spread) and that orbit and Twiss parameters are under reasonable control over a rather larger range so that energy recovery can be successfully executed. Initial results of the geometric aberrations indicate that the transverse phase space remains regular out to 100 times the nominal emittance (100 mm-mrad normalized) across a moderately large momentum range (±2%), indicating the core beam will remain undistorted, halo will propagate cleanly, and the system should show reasonable freedom from orbit dependences in the optics. Without collective effects (i.e. space charge and CSR) the transverse emittance grows by 0.5% (1.5%) in the vertical (horizontal) plane.

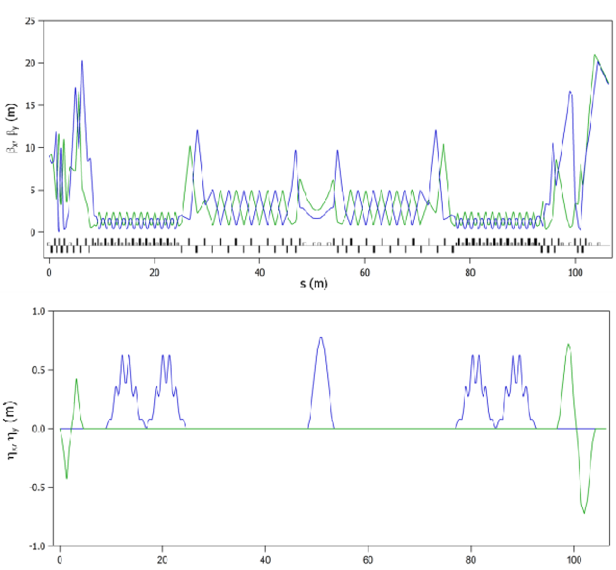

Figure 3: Beta functions (top) and dispersion (bottom) through the low-energy recirculator.

COLLECTIVE EFFECTS

Issues with collective effects include all those associated with ERLs compounded by the challenge of preserving the CW electron drive beam brightness required by short wavelength FELs. The impact of space charge, BBU and other environmental wakes and impedances, ISR and CSR, potential for microbunching, intra-beam and beam-residual gas scattering, ion effects, RF transients, and halo must all be considered [7].

Initial tracking through the low energy recirculator including CSR effects in elegant [8] shows evidence of multibunching (see Fig. 4) [9]. However, because the bunch will be rotated 90° in longitudinal phase space ("parallel-to-point focusing"), the energy modulations are projected onto the time axis and the current distribution at the wiggler is not degraded by modulations.

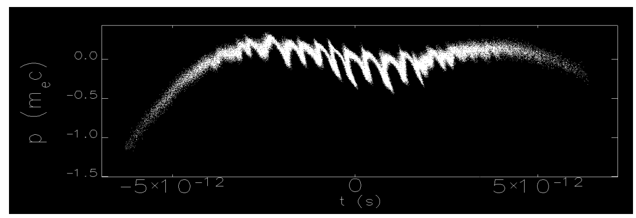

Figure 4: Longitudinal phase space at the exit of the low energy recirculator (chirp removed) with CSR on.

SUMMARY

A proof-of-principle design for an emittance preserving recirculator has been described. The high energy recirculator will follow the same design principles and will include an embedded bunch compressor. While it presents unique design challenges, JLAMP provides a paradigm for an electron beam driver utilizing re-circulation and energy recovery to drive short wavelength FELs.

ACKNOWLEDGEMENTS

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