USE OF MULTIPASS RECIRCULATION AND ENERGY RECOVERY IN CW SRF X-FEL DRIVER ACCELERATORS*

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Abstract

We discuss the use of multipass recirculation and energy recovery in CW SRF drivers for short wavelength FELs. Benefits include cost management (through reduced system footprint, required RF and SRF hardware, and associated infrastructure - including high power beam dumps and cryogenic systems), ease in radiation control (low drive beam exhaust energy), ability to accelerate and deliver multiple beams of differing energy to multiple FELs, and opportunity for seamless integration of multistage bunch length compression into the longitudinal matching scenario. Issues include all those associated with ERLs compounded by the challenge of generating and preserving the CW electron drive beam brightness required by short wavelength FELs. We thus consider 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, as well as the effect of traditional design, fabrication, installation and operational errors (lattice aberrations, alignment, powering, field quality). Context for the discussion is provided by JLAMP, the proposed VUV/X-ray upgrade to the existing Jefferson Lab FEL.

RATIONALE FOR USE OF RECIRCULATION/ENERGY RECOVERY

Figure 1 depicts a figurative "conventional" short-wavelength FEL. In this system, multiple interleaved stages of acceleration and bunch compression are used to generate an appropriately configured set of drive beams, which are then distributed amongst multiple FEL systems using fast kickers or RF deflecting cavities.

Systems with this architecture leverage available excellent linac beam quality to provide bright drive beams to FELs, with commensurately good FEL performance. Such systems are however costly because of the need for a full-energy linac, supporting infrastructure (cryogenic systems and high-energy/power beam dumps), and RF drive for high power electron beams. In addition, "linear" systems of this type typically use chicane-based bunch compressors. It is therefore difficult to compensate higher-order distortions in the electron beam longitudinal phase space without use of harmonic RF systems – forcing costs even higher and imposing aperture constraints and impedance burdens.

Figure 2 presents an alternative concept, based on the use of a recirculated [1] and/or energy recovered [2] linac. In this system, a single linac segment is used for all stages of acceleration; recirculation arcs allow "reuse" of the linac, and also provide momentum compactions to perform staged bunch compression. As there is considerable freedom in the choice of geometry, nonlinear compensation can be included in this magnetic transport [3], precluding any need for harmonic RF.

Cost control is the primary driver for the use of recirculation: such systems balance linac cost (large but $\propto$1/(number of passes)) against beam transport costs (low, but growing with number of passes) to reach an optimum. Figure 3 presents a rudimentary cost comparison for a notional 10 GeV facility [4]; the cost minimum is shallow, but savings provided by recirculation are evident.

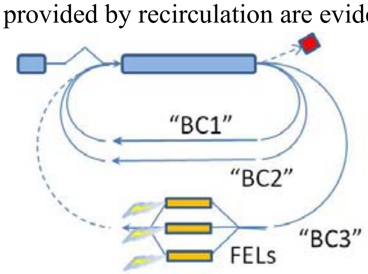

Figure 2: Recirculated/Energy Recovered FEL –Source beam is merged into linac; momentum compactions of recirculators (BC1, 2, and 3) compress bunch. Energy recovery (dashed line) can be implemented as needed

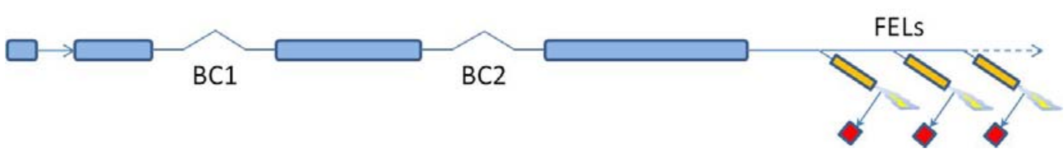

Figure 1: "Conventional" FEL – comprising source, preaccelerator, first stage of bunch compression (BC1), initial acceleration, second stage of bunch compression (BC2), acceleration to full energy, distribution of drive beam to FELs.

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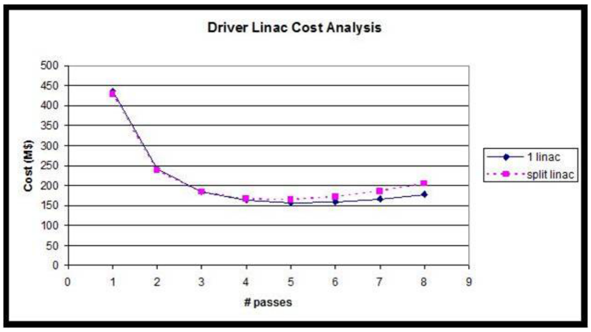

Figure 3: Cost vs. N_{passes} for multipass system.

In addition to cost savings, recirculated systems possess considerable operational flexibility, as the transport provides opportunity for nonlinearly compensated bunch length compression and transverse phase space management. Recirculation also alters machine footprint (short/wider), moving it to geometries simplifying diagnostics, stabilization, feedback, and synchronization.

Additional cost and operational advantage can be obtained through the use of energy recovery, particularly for systems with high power drive beams. The appropriate cost optimization in this case is performed by comparing the incremental cost of the additional required beam transport (modest, but one-time, though increasing with energy recovery and higher energy) against the cost of RF drive (expensive, and persisting as an operational cost) required for high energy/current [5]. Such analyses indicate that not only construction costs – but also the cost/delivered photon – is significantly reduced due to the improvements in wall-plug power efficiency provided by energy recovery. This is to be coupled as well to the operational advantages inherent in the radiation control provided by having only a low-power (low energy) exhaust electron drive beam.

CHALLENGES IN ERL-BASED SYSTEMS

ERLs, as linac-driven systems, produce very high brightness beams; the use of energy recovery also enables them to produce extremely high power beams. They are thus susceptible to problems associated with any of the beam-dynamical phenomena associated with bright, high power beams. These have been discussed in detail in the literature [6]; here we simply note that they typically lead to performance limitations in one of three ways: beam quality may be unacceptably degraded, the beam may – through either beam loss or by way of interaction of the beam current/charge with the environment – deposit unacceptable amounts of power into the accelerator infrastructure, and/or the beam may become unstable. Table 1 categorizes several of these effects and outcomes.

AN EXAMPLE SYSTEM: JLAMP

Overview of System Concept

JLAMP [7] is a proposed upgrade to the existing Jefferson Lab IR/UV FEL facility. It comprises a high-brightness CW injector, a beam-quality conserving merger injecting beam into a multi-pass 300 MeV ERL consisting of three high-gradient (100 MV gain) cryomodules. The system utilizes two transport lines (at 300 MeV and 600 MeV) to recirculate the beam for acceleration and recovery. The 300 MeV transport common to both accelerating and decelerating beams, while the 600 MeV transport accommodates only full energy beam. Both lines have adjustable linear and nonlinear momentum compactions (M_{56}, T_{566},...) so as to provide required flexibility for longitudinal matching of the beam to the wiggler (high peak current) and management of the longitudinal phase space during energy recovery (energy compression).

Table 1: Recirculator/ERL Beam Physics Challenges

Issue	Source	Potential Outcome
space charge	bunch charge	inadequate source brightness, beam quality degradation; power deposition (halo, scraping)
beam break-up (BBU)	higher order mode (HOM) impedances	instability; power deposition (from propagating modes)
beam-environment interaction	other wakes, impedances	beam quality degradation, power deposition, instability
beam collisions with remnant gas	ions, gas scattering	beam quality degradation, power deposition (halo, scraping)
Touschek, intra-beam scattering	intra-bunch collisions	beam degradation, power deposition (halo, scraping)
halo	various	power deposition (beam loss)
Coherent Synchrotron Radiation (CSR)	bunch self-interaction (bunch charge, wake)	beam quality degradation, power deposition, microbunching gain
Incoherent Synchrotron Radiation (ISR)	quantum excitation	beam quality degradation, power deposition
engineering tolerances, fabrication errors, timing, synchronism	alignment, powering, magnet field quality,...	beam quality degradation, power deposition (halo formation)
RF drive	transient beam loading	Instability

Table 2 compares JLAMP parameters to those of the existing system; Figure 4 shows a JLAMP concept in the existing vault. Subsequent discussion focuses on principle initial challenges in execution of the design of the system.

Table 2: JLab IR/UV *vs*. JLAMP Parameters

	IR/UV	JLAMP
Bunch charge (pC)	135	200
Bunch rep. rate (MHz)	75	4.68
Average current, max (mA)	10	1
Norm. transverse emittance at FEL (μm)	10	1
Longitudinal emittance at FEL (keV ps)	60	50
Energy spread at FEL (% rms)	0.4	0.1
Bunch length at FEL, rms (fs)	150	83
Bunch energy (MeV)	135	600

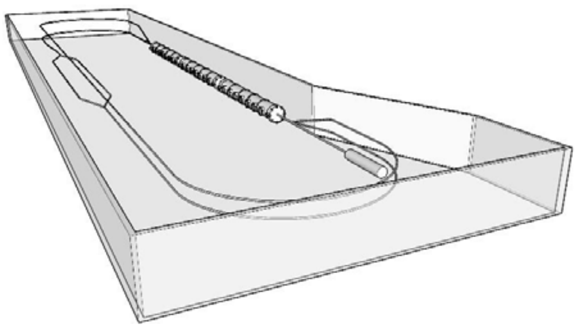

Figure 4: Conceptual Layout in Existing Facility

Electron Source and Injector

JLAMP requires unprecedented CW performance and thus poses a challenge for the electron source and injector. Initial designs use the VHF normal-conducting cavity gun developed by Lawrence Berkeley Laboratory [8] operating at 187.5 MHz – a sub-harmonic of the linac 1.5 GHz fundamental. The cathode gradient is 20MV/m, producing a 750keV beam. The low frequency results in single bunch properties similar to those from a DC source. Experience with DC guns thus guides the injector design: 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 750MHz booster cavities; these capture the low energy beam without distorting the longitudinal phase space, and accelerate it to 10MeV.

Longitudinal Matching Scenario

Careful longitudinal matching is needed to preserve beam quality and deliver to the FEL a beam with the proper momentum spread and peak current; the FEL exhaust beam must also be matched to avoid beam loss during recovery. Use of one stage of compression (with an isochronous 300 MeV arc) appears to avoid degrading effects (*e.g.*, parasitic compressions) during transport to the wiggler, produce the required peak current with tolerable momentum spread, and accommodate the energy compression needed for loss-free recovery [9].

As elsewhere [10], we inject a long, low-momentum-spread bunch (to mitigate space charge). Acceleration on the rising part of the RF waveform induces a phase-energy "chirp" that – with the recirculator compaction – compresses bunch length. The isochronous 300 MeV transport is "transparent"; the 600 MeV beam line provides all bunch length compression.

The process is reversed for energy recovery: 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.

Beam Quality Preservation During Acceleration

PARMELA modelling of JLAMP with space charge indicates that beam quality is preserved by proper choice of injection transverse match [11]. Figure 5 show the dependence of emittance after one pass on choice of injected Twiss parameters. A range of values (red region) avoid emittance dilution; the optimum solution is chosen by comparing betatron functions during transport through the linac and selecting values that are not large (more than a few tens of meters), the machine will otherwise be error-sensitive and instability-prone (e.g. BBU) due to large turn-to-turn transfer matrix element values.

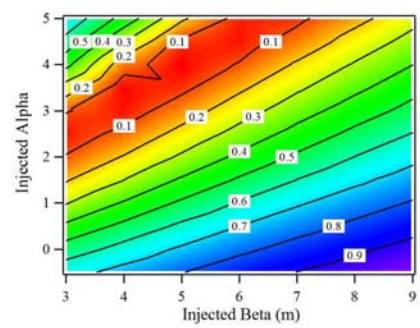

Figure 5: Variation in emittance (mm-mrad) at 300 MeV as function of choice of Twiss parameters at injection.

Recirculator

The recirculator is designed to mitigate effects of ISR and CSR and to provide acceptance for the FEL exhaust beam during energy recovery [12]. It uses an achromatic vertical step (Figure 4) to separate passes at the end of the linac; it then recirculates each pass using individual FODO transport arcs. These are configured as second-order achromats, allowing compensation of chromatic aberrations and adjustment of compactions through nonlinear order. Beams are recombined using a "staircase recombiner" similar to those in CEBAF [13].

Momentum compactions of each transport module are coordinated to provide isochronous transport on the first (and third) pass(es), bunch length compression before the wiggler, and energy compression during energy recovery, all while avoiding beam-quality-degrading parasitic compressions. Initial studies [14] indicate that CSR effects, though manifested as microbunching in simulations (Figure 6), have only limited impact on beam quality, with ~10% increase in emittance of a 1 mm-mrad 200 pC beam during recirculation at 300 MeV. These effects are yet to be studied at full energy.

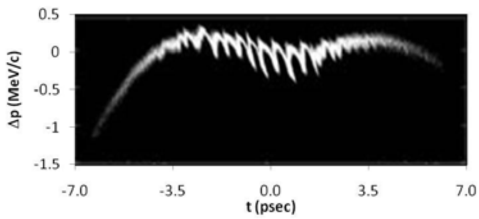

Figure 6: `elegant` [15]-simulated longitudinal phase space of 200 pC beam after acceleration to 300 MeV and isochronous recirculation including CSR effects (chirp has been extracted from data).

BBU

BBU is of concern in any recirculated linac, and is exacerbated by the use of multiple passes. The instability threshold current scales roughly as $M_{ij}(1/N_{pass}^2)$ (where M_{ij} is the turn-to-turn transfer matrix) [16]. M_{ij} is not overly sensitive to N_{pass}: though the higher-pass focusing degrades as N_{pass} increases, the shorter linac offsets the focusing reduction. JLAMP parameters are not overly challenging; 1 mA in a multi-pass ERL is to be compared to the modelled 1 A threshold in a number of "single"-pass systems [17]. Detailed simulation analysis using observed HOM (R/Q) is underway.

REMARKS ON UPGRADES; CONCLUSIONS

JLAMP can be readily upgraded to be a 3-pass recirculated linac; all that is required is that an additional half-RF-wavelength be added (or removed) from the 600 MeV transport. In this case, the beam will – instead of being recovered in energy - be accelerated on a third pass through the linac to ~1 GeV final energy, with beam available for delivery to an external beam line at full energy. As in "ERL mode", the recirculation transport can be configured to give appropriate multistage bunch compression. In the three-pass configuration, it is relatively straightforward to generate multiple beams – and direct them to multiple FELs – through the use of RF separation as used in the CEBAF accelerator [18].

As a "prototype" fourth-generation light source, JLAMP is both a user facility and a proof-of-principle for ERL-driven FEL. Once validated, this paradigm can be extended to serve numerous FELs at multiple – and shorter – wavelengths. The notional "Generic Energy Recovered Bisected Asymmetric Linacs" (GERBAL, Figure 7) [19] is a concept for such a system. Use of a split linac with unequal gains embeds a preaccelerator within the ERL, offers improved performance, and allows use of independent pass-to-pass transport throughout the machine. This increases operational flexibility and avoids common transport of multiple passes. An RF-separator based switchyard splits multiple beam trains, directing the beams to various FELs, then recombines them for energy recovery – thus retaining the wall-plug-power efficiency characteristic of ERL architectures.

Recirculated linacs and multipass ERLs thus have potential as high-performance, operationally flexible FEL-based fourth-generation light sources. Numerous challenges – particularly related to preservation of beam quality during acceleration and beam handling processes, and the management of halo associated with high power CW beams – remain, and are undergoing investigation.

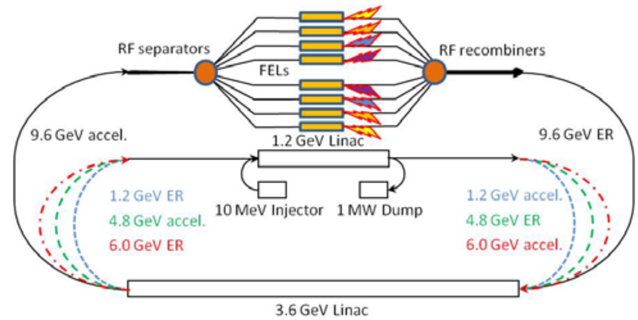

Figure 7: A ~10 GeV "GERBAL" multipass FEL driver; independent transport lines for each pass provide operational flexibility. RF separation/recombination of beams allows simultaneous service to several FELs.

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