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ARCHITECTURAL CONSIDERATIONS FOR RECIRCULATED AND ENERGY RECOVERED HARD XFEL DRIVERS*

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Abstract

A confluence of events motivates discussion of design options for hard x-ray free electron laser (XFEL) driver accelerators. Firstly, multiple superconducting radio-frequency (SRF) driven systems are coming online (European XFEL), in construction (LCLS-II, SCLF), or in design (MARIE); these provide increasing evidence of the transformational potential they offer for fundamental science with its concomitant benefits. Secondly, successful operation of 12 GeV CEBAF [1] validates use of recirculation in the design of high energy SRF linacs. Thirdly, advances in the analysis and control of various effects – including coherent synchrotron radiation (CSR) and the microbunching instability (μBI) – have been recently achieved. Taken collectively, these developments offer opportunities to extend facility science reach, reduce cost, provide multiplicity (*i.e.,* support numerous FELs operating over a range of wavelengths), and enhance scalability and upgradability (to higher powers and energies). We discuss the relationship amongst the various threads, and indicate how they inform design choices for the system architecture of an option for the UK-XFEL [2] – that of a staged multi-user X-Ray FEL and nuclear physics facility based on a multi-pass recirculating SRF CW linac.

OVERVIEW

Energy-recovered [3] and recirculated [4] superconducting [5] accelerators were first envisioned a half-century ago, and the use of both as FEL drivers has been subsequently explored [6-9]. Such accelerators may be cost/performance optimized in many ways, including the choice of RF architecture (SRF or NCRF, pulsed or CW), use of recirculation, and desired multiplicity of FELs. Choices amongst these options are driven by end-user requirements; here, we explore the implications of service in a single facility to a range of users, with pulsed or CW photon beams from the EUV to hard X-ray regimes.

SYSTEM REQUIREMENTS

FEL driver accelerators share a common suite of requirements that have been detailed in previous discussions [6-9]. The system must produce beam(s) at the energy (or energies) required to drive the FEL(s). Bunch charge, repetition rate, and bunch time structure must be adequate to provide the power and timing required by users. The system must generate beams of adequate brightness, configure them appropriately for each FEL, and preserve beam quality through acceleration, transport (including, possibly, multiple recirculations), and – if so required – energy recovery. These requirements must be met while satisfying constraints such as finite accelerator acceptance, RF drive limitations, and operational implications of service to multiple users. Additionally, appropriate stability issues must be addressed, including collective effects, interaction with the accelerator environment, and implications of phenomena such as halo.

BEAM FORMATION

Various injector designs provide "proof of principle" solutions for CW XFEL drivers. An operational demonstration is given by the Cornell injector [10], which offers the requisite bunch charge, repetition rate, energy, beam brightness, and cathode lifetime needed for high power/energy multi-FEL facilities.

LONGITUDINAL MATCHING

Longitudinal matching is a defining feature of recirculated architectures, in that it defines how the injected beam (of low momentum spread and long bunch length, to mitigate collective effects) is manipulated during acceleration, transport, delivery to the FEL and energy recovery (should that be a requirement). Longitudinal matching solutions have been in use in CW systems for over two decades [11]; the influence of collective effects, such as space charge, CSR, and the μBI have more recently been successfully addressed [12, 13]. Very recently, caustic methods applied in other dynamical systems have been used for accelerator longitudinal matching, providing a powerful tool for developing robust solutions [14].

In addition to beam quality preservation, the longitudinal match is of critical importance in defining the RF dynamics [15]. For example, choices of linac operating phase and transport momentum compaction values influence RF transient behavior. Further choices are driven by phase space distortion such as RF curvature, which may be corrected using harmonic RF and/or DC magnetic compensation. Pulsed FEL drivers have successfully implemented harmonic correction/linearization [16], while

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to date all operating SRF FEL drivers have employed only beam-transport-based schemes [17].

RECIRCULATION : OPTIMIZATION AND INSTABILITIES

The successful commissioning and initial operation of 12 GeV CEBAF [1] provides an operational demonstration for large-scale application of SRF technology in a recirculated architecture. Scaling of such solutions to higher currents will involve extensions of existing experience. The first of these involves the beam break-up (BBU) instability; this effect is well understood and manageable given measurements performed in the JLab IR Upgrade FEL-ERL [18], which (indirectly) observed thresholds of hundreds of mA, and tuned the system to establish absolute stability. SRF cavity design now regularly provides control of BBU at the levels required [19, 20].

Choice of RF frequency has historically depended on prior work, but tools allowing broad cost/performance analysis are available [21] which indicate that a broad optimum exists near 800 MHz.

Design and operational experience with multiple SRF systems indicates that a full system-wide optimization is required. In particular, the "best injected beam" does not necessarily lead to the "best delivered beam", because an overly-bright beam can degrade in the linac front end [22]. A design-time optimization of the injector/linac interface sets the optimum injected beam parameters [7].

Linac focusing structure is a prominent feature of this process, and provides performance constraints. As the number of recirculations, energy and length, increase, focusing on higher passes becomes weaker, resulting in larger lattice beam envelopes, with consequent increases in sensitivity to errors and collective effects. Appropriate choices of system configuration, such as the use of asymmetrically split linacs [23] can be palliative.

Use of recirculation provides significant cost-optimization, but also introduces potential for degradation of beam quality. Challenges include incoherent synchrotron radiation (ISR) and CSR, as well as instabilities such as the μBI, which involve combinations of longitudinal space charge (LSC) and/or CSR and bunch length modulation with energy via the transport system momentum compaction. ISR has been recognized for half a century as an issue in recirculated systems [5], and have been addressed in system designs [24] through the use of bend radius and low-quantum-excitation lattice designs. Recently, methods for control of CSR- and μBI-driven degradation have been developed [25-27] and provide means of providing adequate beam quality while implementing recirculation-based system architectures for XFEL drivers.

COMPRESSOR SYSTEMS

Bunch compression is a critical challenge for short-wavelength FEL driver designs, regardless of system architecture. Recent work [28] provides insight on the limits of, and an existence proof for, multi-GeV full-energy compressors that would be useful for implementation in a multi-FEL facility. Results at GeV scales [29-31] provide compact configurations and in combination with emittance-preserving recirculation transport.

USE OF ENERGY RECOVERY

Recirculation and energy recovery are simply cost optimization measures, in which linac and RF drive are traded for beam transport until an optimum of cost and performance are achieved. Tools for performing such optimizations exist and have been applied in example cases [21], providing guidance as to the applicability of either for specific facility design parameter sets. Recirculation becomes increasingly attractive for higher energy systems, so as to save on costs of linac hardware; energy recovery is similarly attractive at higher currents, as it saves significant expenditures on RF power.

ONGOING CHALLENGES

Though progress has been made on all aspects of the architecture of recirculated [1] and energy recovered SRF linacs [32, 33], challenges remain. Legacy systems have operated at only 1 MW full-energy beam power, and were thus largely able to run without full understanding and control over beam halo [34]. Extrapolation to 10 MW and higher will require suppression of localized beam losses to a few parts per million. This has as yet not been demonstrated in non-equilibrium systems.

Existing CW SRF systems have directly demonstrated BBU stability at only a fraction of the multi-pass in-linac current needed, although CBETA has this as a primary goal [35]. Heating from collective effects, such as THz emission, resistive wall losses, and RF heating has proven problematic in legacy systems [36] and will have greater impact at higher energy and current. No systems now in operation or under construction provide a platform for testing in a multipass architecture.

There have been few demonstrations of ERL operation in which the full-energy "virtual" beam power exceeded installed RF drive, and none of these involved multiple passes and/or fully common transport for acceleration and recovery. Large system designs rely on both, despite operational experience indicating heightened risk and degree of difficulty. The impact of increased "dynamic range" (the ratio of full to injected beam energy) is poorly characterized. In ERLs error sensitivity increases when perturbations at high energy are adiabatically anti-damped on deceleration.

STAGED UK-XFEL SYSTEM PROPOSAL

There is an ambition to build an XFEL in the UK in the coming decade [2]. Specifications are still evolving, however many are not compatible with normal conducting linac technology e.g. user requests have included >100 kHz repetition rate ~10 keV pulses with laser / XFEL synchronisation less than 1 fs. Superconducting linac technology is therefore explored as an option. To

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minimise facility cost and maximise scientific opportunity over a likely 30-year lifespan, two stages of accelerator development are proposed. Initial construction would be an N-pass recirculator driving a suite of short-wavelength FELs, this would be followed by a second stage where N-pass energy recovery (ER) is enabled with only the addition of transport beamlines and no further civil construction. This staged philosophy ensures that baseline facility requirements are met with lowest risk, whilst the additional (and unprecedented) capability enabled by high average beam current is not precluded, merely deferred to a second stage when experience has been gained.

In the ER-enabled second stage, transform limited pulses would be possible at ~10 keV through the deployment of XFELO / RAFEL type FEL's at multi-MHz repetition rates. Harmonics of the fundamental wavelengths up to ~1 MeV would have sufficient average power to be applicable to novel materials science. Narrowband ($<10^{-3}$) gamma sources from MeV to multi-GeV would be achievable through inverse Compton scattering on the XFELO beam [37]. Internal target dark matter searches and radio-isotope production would also be promising applications of such a facility.

The first consideration in design of an N-pass recirculating system (whether or not ER is implemented) is the choice of topology. This is because unlike rings and single pass linacs, there is additional freedom in the basic layout of the accelerator. An obvious choice would seem to be a symmetrically bisected linac, such as the layout of CEBAF. If this is chosen, there is still freedom whether to inject the spent beam for recovery into the first or second accelerating linac. Choosing to inject into linac-2 is preferable as this then separates the accelerating and decelerating beams in energy at all locations, allowing independent control of the phase spaces from pass to pass (unfortunately not possible in the proposed ER@CEBAF experiment [38] where we must transport both accelerating and decelerating passes in the same beam line leading to multiple restrictions on operation). An asymmetrically-bisected linac [23], although less efficient in terms of tunnel packing fraction, is superior optically as it mitigates the low beam energy constrained focusing. Another alternative is to symmetrize an asymmetrically bisected linac. This is achieved by splitting it into one half-linac on one side of a racetrack and two quarter-linacs on the other side, all injection / extraction are then placed between the two quarters. This has all the advantages of the asymmetric topology, but retains the original tunnel packing fraction and symmetrizes all optics in the spreader / recombiner sections, simplifying the design.

N, the number of recirculation passes, is to be cost optimized with regard to both non-ER and ER incarnations at the design stage. It should be noted that N=1, a single linac, is part of this optimisation. The relevant trade-off is of linac and cryogenic cost versus switchyard, arc and tunnel cost. The primary physics limitation comes from ISR - usually considered in terms of quantum excitation of energy spread that leaks via dispersion into slice emittance growth. In a ~10 GeV scale recirculated XFEL it turns out that the longitudinal emittance degradation is the limiting factor – i.e. we are concerned with the slice energy spread increase itself. The design parameter is thus the arc radius required to avoid growth to a specified relative slice energy spread at the FEL. This scales as energy to the power 2.5. In addition, through the longitudinal phase space shearing used to compress the bunch, this translates directly to a limit on the peak current achievable. In our example, considering only the peak current, we should pick an arc radius of 150 m to ensure the ISR limit lies above 1.5 kA. One positive effect is that μBI will be fully suppressed as the ISR in the arcs Landau damps it away. Residual energy chirp would be mitigated by dechirping (in common with single pass SC linacs), symmetrized topologies allow further mitigation by compressing before the final acceleration as the final arc need not necessarily be at the top energy.

Picking a topology, an energy and tolerable peak current and slice energy spread sets the arc size required and therefore the cost of the facility. Initial cost estimates are that for an 8 GeV machine, the optimum lies at 3-passes with a saving of ~ 35% over a single-pass linac. An additional 10% investment would enable ER in a 3-up / 3-down configuration, leading to a final facility capable of 100 MHz repetition rate that is cheaper than a single linac (which is only capable of ~1 MHz rep. rate) by ~ 25%.

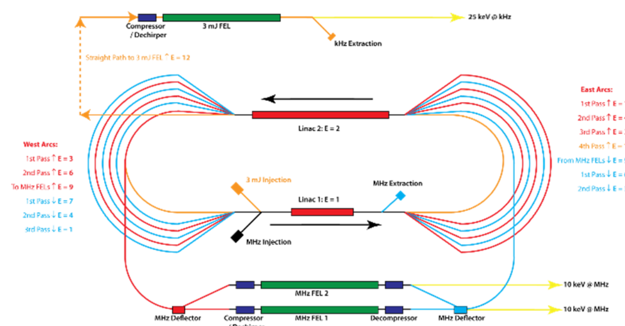

Figure 1: Option for UK-XFEL based on 3-pass recirculating SC linac. We show the ER-enabled second stage driving two multi-MHz rep. rate FELs at 10 keV. Also shown is 4th non-ER low current pass for additional high pulse energy FEL at 25 keV.

CONCLUSIONS

Numerous recent advances in accelerator design and operation motivate consideration of recirculation and energy recovery in ~ 10 GeV scale CW systems as the basis for XFEL and nuclear physics facilities. We present an option for the UK-XFEL as an example of this.

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