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USING ER@CEBAF TO SHOW THAT A MULTIPASS ERL CAN DRIVE AN XFEL*

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Abstract

A multi-pass recirculating superconducting CW linac offers a cost effective path to a multi-user facility with unprecedented scientific and industrial reach over a wide range of disciplines. We propose such a facility as an option for a potential UK-XFEL. Using Energy Recovery would enable multi-MHz FEL sources, for example, an X-ray FEL oscillator or regenerative amplifier FEL. Additionally, combining with external lasers and/or self-interaction would provide access to MeV and GeV gamma-rays via inverse Compton scattering at high average power for nuclear and particle physics applications. An opportunity exists to demonstrate the necessary point-to-parallel longitudinal matches to drive an XFEL and successfully energy recover at the upcoming 5-pass up, 5-pass down Energy Recovery experiment on CEBAF at JLab termed ER@CEBAF. We show candidate matches and simulations supporting the minimal necessary modifications to CEBAF this will require. This includes linearisation of the longitudinal phase space in the injector and a reduction in the dispersion of the arcs, both of which increase the energy acceptance of CEBAF. We expect to commence initial tests of these adaptations on CEBAF during 2021.

INTRODUCTION

ER@CEBAF is a unique opportunity to explore the application of a multi-pass superconducting ERL to drive a continuous wave XFEL. Such a machine would be capable of repetition rates (and therefore average powers) well beyond that envisaged for contemporary XFEL projects such as the European XFEL CW upgrade [1], LCLS-II [2] and SHINE [3], whilst requiring fewer accelerating structures, having a smaller footprint and lower cost. The simultaneous high average beam power and brightness also makes it attractive to use the electron beam to drive narrowband MeV to GeV gamma-ray sources via inverse Compton scattering [4]. These capabilities are currently under study as part of the UK-XFEL facility proposal [5]. The potential to adapt CEBAF to address similar topics has been explored in various guises over the years [6–9] however none have come to fruition until now.

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ER@CEBAF [10] is an experiment to demonstrate a multipass ERL at GeV scale whose intention is to inform the design of future ERL based high energy physics facilities [11]. The adaptations to CEBAF needed to show this comprise one phase-shifting chicane at the exit of arc 10 and an ER dump at the end of the south linac, the layout as shown in Fig. 1. To demonstrate the beam dynamics required to drive an FEL, only relatively minor further modifications are needed, making ER@CEBAF a golden opportunity to demonstrate how ERLs can expand accelerator applications. In order to drive

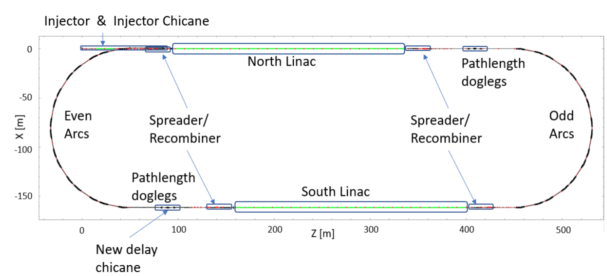

Figure 1: Layout schematic of ER@CEBAF.

an XFEL, one must compress the bunch to a peak current of a few kA whilst maintaining energy spread no greater than 10^{-4}, without significant transverse emittance degradation. Modern photoinjectors now routinely satisfy emittance requirements, but with relatively long bunch lengths, therefore the bunch must be compressed within the accelerating transport. Conversely, to successfully energy recover spent bunches, one must decompress and paint them onto the correct phase interval of the decelerating RF. Together, this scheme is termed a point-to-parallel match. The two ingredients required for this are 1) acceleration and deceleration off-crest/trough to modify energy chirp of the bunch and 2) systems that magnetically compress and linearise the bunch between acceleration/deceleration stages. This implies that the transport must have larger energy acceptance than formerly required for regular CEBAF or ER@CEBAF operation.

ERL OPERATION CONSTRAINTS

An ERL can be classified as common transport if the beam traverses the same arcs during acceleration and deceleration. If instead the beam only sees each of the arcs once from injection to dump it is a separate transport ERL.

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An ERL brings operational constraints that need to be taken into account during its design. A separate transport ERL must: achieve the target energies at the interaction point and dump, achieve the constrained longitudinal phase space at the interaction point and dump, withstand and transport disruptions at the interaction point with very low losses, and, at every point in the system, the beam energy spread must fit within the energy acceptance. A common transport, such as ER@CEBAF, has the additional constraint of requiring all intermediate energies to be the same accelerating and decelerating.

In order to ensure the ERL's functionality, we can relate each of these constraints to machine parameters: i) centroid energy is linked to our choice of rf phase, ii) energy spread constraints depend on arc momentum acceptance and our capability to compensate for generated beam chirp, iii) high peak current target at the interaction point is directly controlled by the top energy arc longitudinal dispersion, R_{56} as well as our linearisation scheme and iv) desirable low current during transport and into the dump can be controlled with the pre-compression occurring in the injection chicane and the intermediate arcs R_{56}.

PROPOSED MODIFICATIONS

RF Phase

The operation of an ERL is based around the control of path lengths between successive passes through the rf cavities. At the defined top energy transport, a path length change corresponding to a π phase shift into the next rf cavity results in deceleration and thus energy recovery from the spent beam. With top energy of 7 GeV we must take into consideration in our energy balance the energy lost to synchrotron radiation, about 14 MeV. Without other sources of energy for the beam, like harmonic cavities, to top up the beam energy pass by pass, if the beam makes a π phase shift into decelerating mode the energy mismatch between accelerating and decelerating beams while traversing the same arc may exceed the energy acceptance of our transport system. Alternatively, we can change the decelerating rf phase by deviating from the π phase shift and so reduce our energy recovery efficiency to guarantee adequate energy correspondence between accelerating and decelerating beams traversing the same arcs as shown in Fig. 2.

In principle, arc path lengths could be set up such that on a pass by pass basis, the difference between the energy gained accelerating and the energy recovered decelerating corresponded to the energy lost to ISR. This however would significantly change the energy ratios between the arcs requiring a redesign of the spreader-recombiner systems as well as imprinting pass by pass a chirp into the beam that can only be compensated for with parasitic compressions where the bunch goes through a minimum bunch length while electrons at the head and tail exchange their positions.

The centroid energy condition sets how far off-trough we must decelerate for a given accelerating phase. At that point

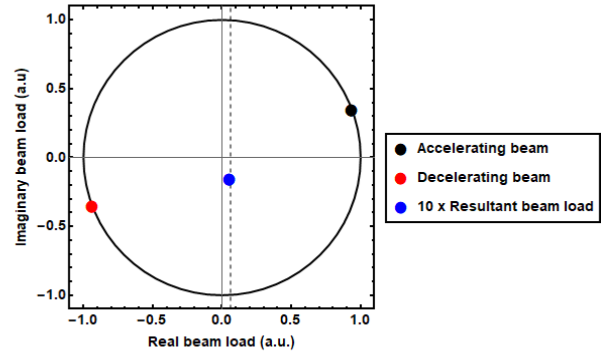

Figure 2: Rf beam load in accelerating passes (black), decelerating passes (red) and resultant (blue). Horizontal position of dashed line represents energy recovery efficiency loss due to energy loss compensation.

it only remains to choose what side of the trough we should decelerate on. The one that is closest to a π shift from the accelerating phase is the one that ensures chirp compensation such that the beam's energy spread can be made to fit in the arc energy acceptances.

Injector Chicane

In a common transport ERL, the beam traverses the same arcs accelerating and decelerating. Therefore, to facilitate longitudinal manipulations, we preferably employ sections before injecting into the ERL loop and the top energy arc, as the beam only goes through them once. We propose an addition of two pairs of sextupoles into the injection chicane to gain control over the second-order horizontal dispersion, T_{166}, and second order longitudinal dispersion, T_{566}. The range of T_{566} values available is shown in Fig. 3. This control over the second-order longitudinal dispersion in the injector chicane will allow us to pre-linearise our bunch without having to only rely on the arcs.

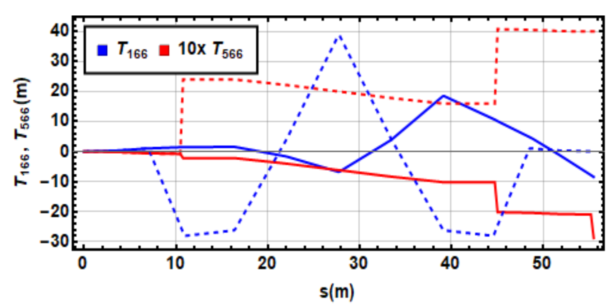

Figure 3: Second-order horizontal (red) and longitudinal (blue) dispersions in the injector chicane with (dashed) and without (solid) additional sextupoles.

Arc Modifications

A longitudinal match like the one required to drive an FEL where the bunch is to be compressed and decompressed requires accelerating off-crest. This increases the energy

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spread which together with residual energy mismatches in the arcs between accelerating and decelerating beams requires an increase of the arcs energy acceptance, limited by the peak dispersion values. In order to increase the energy acceptance of the arcs, the polarities of arc quadrupoles in charge of dispersion control are flipped [12], trading high dispersion peaks for larger vertical twiss functions. This results in an overall reduction of peak dispersion values in the arcs of a factor of 2 with the exception of Arc 1 where, in order to maintain a zero longitudinal dispersion, dispersion peaks are only reduced by a factor of 1.6 as shown in Fig. 4.

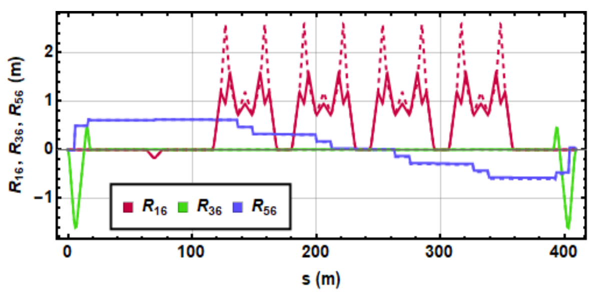

Figure 4: First order horizontal (red), vertical (green) and longitudinal (blue) dispersion before (dashed) and after (before) reduction of the peak dispersion.

Longitudinal Match

The X-FEL longitudinal match that we want to replicate revolves around a bunch compression at top energy to achieve the maximum current possible to drive our fictitious X-FEL at the exit of Arc 10. In order to preserve beam quality during transport from the injector to the interaction point, the bunch length must be kept long to minimize the impact of collective effects. During deceleration, the bunch undergoes an anti-damping process. Therefore, the bunch must be decompressed and chirp compensated to remain within the arcs aperture.

Since ER@CEBAF is a common transport ERL and thus arc parameters are the same accelerating and decelerating we employ a semi-analytic method, extended from the one by Zagorodnov and Dohlus [13] to include ERL operation constraints to find a range of working machine parameters shown in Table 1. In this model, the energy distribution of the initial bunch is approximated as

$$\delta_0(s) = \delta_0' s + \frac{\delta_0''}{2} s^2 + \frac{\delta_0'''}{6} s^3 , \qquad (1)$$

where s is the longitudinal position of the particles in the bunch. Arc elements are defined as drifts such that

$$s_i = s_{i-1} + (R_{56}^{(i)} \delta_i + T_{566}^{(i)} \delta_i^2 + U_{5666}^{(i)} \delta_i^3) , \qquad (2)$$

where i represents the element index, rf elements are modeled as thin lenses where

$$\delta_i = \frac{(1+\delta_i)E_{i-1} + \Delta E_i}{E_i} - 1 , \qquad (3)$$

and E_i is the beam centroid energy at the i^{th} stage.

Table 1: Alternative Longitudinal Match Solution in Various Arcs

Top arc R_{56} (m)	**Decompressing arc** R_{56} (m)	**Accelerating rf** phase (0° = on crest)
-0.30	0.23 (arc 5)	8°
-0.38	0.22 (arc 8)	8°
-0.44	0.25 (arc 9)	8°
-0.19	0.11 (arc 9)	18°

Choosing to set Arc 9 as the decompressing arc to decompress the bunch immediately after the first decelerating pass and minimize the transport of the fully compressed bunch, and choosing the bunch to have a flat longitudinal profile as it reaches arc 1 decelerating, and considering the achievable longitudinal dispersions in the selected arcs, we obtain the values of R_{56} for arc 9 and arc 10 to be 0.11 m and −0.19 m respectively. This results in a compressed longitudinal phase space after arc 10 as shown in Fig. 5. The prediction from the 1-d model, without energy spread, matches the longitudinal phase space obtained via tracking with Elegant. Further optimization of the peak current can be done by tuning the T_{566} of arc 10.

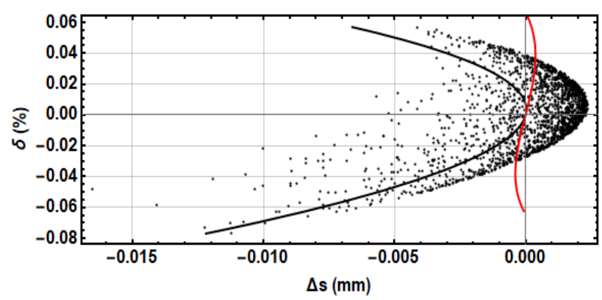

Figure 5: Tracked bunch longitudinal phase space, prediction of the tracked bunch from semianalytical model (black line) and semianalytical prediction after preliminary second order corrections (red line).

CONCLUSIONS

We have shown the operational constraints for an ERL to be a suitable machine to drive an XFEL, as well as the series of modifications we propose to the CEBAF lattice that would provide the right longitudinal match. To first order, this requires a modification of the arcs to increase their momentum acceptance, adequate choice of RF phase and arc path length to be able to manage energy lost to ISR, and finally modifications to arcs 9 and 10 to compress and decompress the electron bunch. In order to further improve our longitudinal match we are working on second order corrections to eliminate the curvature from the compressed bunch while not compromising our capabilities to transport the bunch in the decelerating passes. We plan to commence tests on the proposed changes during 2021.

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