AN ELECTRON BUNCH COMPRESSION SCHEME FOR A SUPERCONDUCTING RADIO FREQUENCY LINEAR ACCELERATOR DRIVEN LIGHT SOURCE*

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Abstract

We describe an electron bunch compression scheme suitable for use in a light source driven by a superconducting radio frequency (SRF) linac. The key feature is the use of a recirculating linac to perform the initial bunch compression. Phasing of the second pass beam through the linac is chosen to de-chirp the electron bunch prior to acceleration to the final energy in an SRF linac ("afterburner"). The final bunch compression is then done at maximum energy. This scheme has the potential to circumvent some of the most technically challenging aspects of current longitudinal matches; namely transporting a fully compressed, high peak current electron bunch through an extended SRF environment, the need for a RF harmonic linearizer and the need for a laser heater. Additional benefits include a substantial savings in capital and operational costs by running on-crest in the afterburner and utilizing all of the available gradient.

INTRODUCTION

A novel bunch compression scheme (or, "longitudinal match") is presented which has the potential to not only avoid implementing technically challenging hardware and operational procedures but also offers substantially reduced capital and operational costs. To understand this new longitudinal match and its benefits, a brief overview of a standard compression scheme utilized in linac driven light sources is given.

STANDARD LONGITUDINAL MATCH

The standard longitudinal match is illustrated in Fig. 1 and consists of the following steps:

1) Accelerate off-crest in L1 to induce a phase-energy correlation along the bunch
2) Use harmonic RF to linearize the longitudinal phase space
3) Implement a laser heater (LH) to increase intrinsic energy spread *(optional)*
4) Partially compress the bunch in BC1
5) Intermediate acceleration in L2
6) Fully compress the bunch in BC2
7) Accelerate to final energy and de-chirp in L3

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Figure 1: Schematic of a conventional linac driven light source and the elements required for a longitudinal match.

NOVEL LONGITUDINAL MATCH

A new longitudinal match, which incorporates into the design a recirculating linac, is shown schematically in Fig. 2. The compression scheme can be described as follows:

1) Inject beam at E_{inj}
2) Accelerate through linac (ϕ_{L1}) to induce a phase-energy correlation along the bunch
3) Perform the first bunch compression and linearization in recirculator arcs
4) De-chirp the beam through linac on the second pass by running near zero-crossing (ϕ_{L2})
5) Accelerate on-crest through the afterburner (ϕ_{L3})
6) Perform the final bunch compression

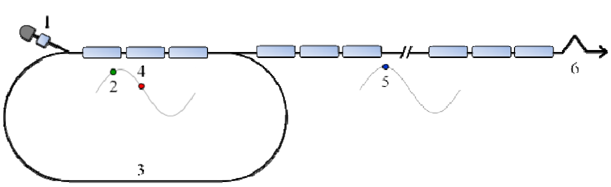

Figure 2: Schematic of the machine topology for a new longitudinal match.

This scheme offers several important advantages:

1) Robust compaction management with recirculator
That is, one can control how much and how quickly the bunch is compressed and provides independent tuning for nonlinear correction through high-order, thereby eliminating the need for harmonic cavities.

2) End the match with the final compression
By ending with a compression, transporting a short, high peak current bunch through the largest section of SRF linac is avoided.

3) On-crest Acceleration through Afterburner
Because the de-chirping is achieved in the second pass through the linac, the beam does not have to run far off-crest in order to remove the correlated energy spread. Furthermore, full advantage is taken of the available SRF gradient which makes for a more efficient/cost-effective machine.

4) *Minimizes the effect of CSR-induced microbunching at the wiggler*
 Unlike the conventional longitudinal match, here the bunch is effectively rotated 90° in longitudinal phase space ("parallel-to-point" focusing). Therefore any energy modulations that arise due to CSR-induced microbunching are converted to temporal modulations. Care still must be taken to mitigate the microbunching instability as this will now affect the final achievable bunch length (peak current). Done carefully however, this has the potential of eliminating the need for a laser heater.

5) *Reduces capital and operating costs*
 By eliminating the need for harmonic cavities, one not only saves on hardware and high frequency RF power sources, but also by not having to buy cavities at the fundamental frequency needed to make up the energy that is lost by deceleration through the harmonic linearizer. Furthermore, since de-chirping is achieved in the recirculating linac, the bunch can be accelerated on-crest through the afterburner, thereby taking full advantage of the available SRF gradient.

This scheme is not without challenges. The success of the longitudinal match is critically dependent on the ability of the recirculator arc to preserve beam quality. Maintaining beam quality through the final compression also presents a challenge.

GREENFIELD DESIGN

The design of any light source is dictated, first and foremost, by the requirements specified at the photon producing device (i.e. wiggler or undulator). The machine lattice serves to take a bunch distribution generated from the source and transform it in such a way that it meets those specifications. The longitudinal match described in the previous section is straightforward conceptually, but when it comes to designing the system, one is faced with a number of variables: the injection energy (E_{inj}), injected bunch length ($\sigma_{t,inj}$), energy gain in the recirculator linac ($E_{L1=L2}$) and the acceleration phase for each pass (ϕ_{L1}, ϕ_{L2}), the bunch length after the first compression ($\sigma_{t,BC1}$), and the energy gain and phase through the afterburner (E_{L3}, ϕ_{L3}). To get a handle on the region of usable parameter space, an analytic model of the longitudinal evolution of the bunch was developed [1]. Expressions for the bunch length, energy spread and centroid energy can be written after each longitudinal "element" (i.e. linac or bunch compressor). Ultimately the absolute energy spread at the photon generator can be written in terms of the design variables. One of the important results that emerged from the model is that, for on-crest operation in the afterburner, the energy spread at the photon generating device is entirely determined by the recirculator. A few comments about the variables:

$\sigma_{t,inj}$: would like to inject a longer bunch to alleviate emittance growth due to space charge
$E_{L1=L2}$: is there an optimal energy gain for the recirculator linac?
ϕ_{L1}: would like to run further off-crest to avoid excessive RF curvature sampled by the bunch
ϕ_{L2}: want to separate beams by energy in the recirculator (i.e. must be < 90°)
$\sigma_{t,BC1}$: subject to analysis of CSR effects, what is the minimum tolerable bunch length in the recirculator? For the sake of argument, assume 0.5 ps (rms).

To ascertain what constraints are imposed by the longitudinal match scheme, contour plots of ΔE_{L2} as a function of $\{E_L, \phi_{L1}\}$ for specific values of $\sigma_{t,inj}$ and ϕ_{L2} were generated. Consider the case for $\sigma_{t,inj}$ = 3.0 ps and ϕ_{L2} = 55° shown in Fig. 3. The shaded region that extends from ±5° denotes a region of operation that is excluded to prevent any part of the bunch falling over crest. Knowing the specification at the photon generator for the absolute energy spread provides guidance for regions in parameter space where the machine can operate. One of the interesting results of this study is that, for a given energy spread specification, having a high gain linac in the recirculator more tightly constrains where you can accelerate on the RF waveform. The parameter space opens up, however, as you go to lower linac energy gains.

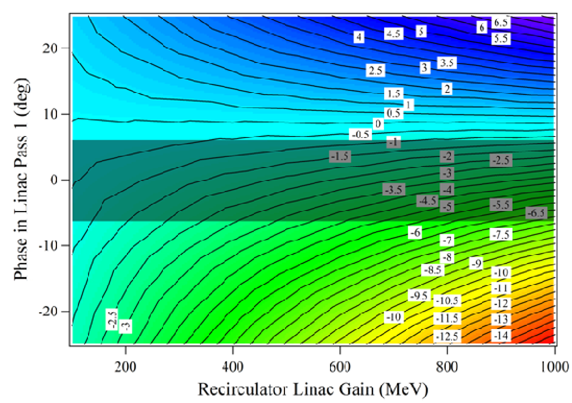

Figure 3: Contour plot showing the absolute energy spread at the photon generator (in MeV) as a function of acceleration phase in the first pass through the linac and of the energy gain in the recirculator linac.

SIMULATION RESULTS

Consider a 1.5 GeV light source operating with a bunch charge of 100 pC. Assume a fundamental RF frequency of 1497 MHz, injection energy of 10 MeV, on-crest operation of the afterburner (ϕ_{L3} = 0°), subject to the requirements that the relative energy spread at the wiggler must be less than 0.1% and the peak current approximately 1 kA [2]. Also assume that we can compress and tolerate a 0.5 ps long bunch in the recirculator. Using the data from Fig. 3 we choose to accelerate through a 300 MeV linac in the recirculator at 17° before crest (represented as a positive angle in Fig. 3).

Using these values a proof-of-principle longitudinal match has been simulated with LiTrack [3] demonstrating the key features of the scheme. LiTrack only tracks particles in longitudinal phase space – no knowledge of the transverse dynamics is required. Furthermore, no collective effects were included (space charge and CSR). Nevertheless, the results achieved were encouraging enough to begin thinking about a more detailed design. A brief description is provided for the screenshots shown in Figs. 4-6:

Figure 4
(a) An injected bunch 3.00 ps (rms) × 15 keV (rms) is injected at 10 MeV.

(b) The bunch is accelerated 17° before crest through the first pass of the linac to a final energy of 297 MeV.

Figure 5
(a) The momentum compactions of the recirculator arc are chosen to both compress the bunch down to 0.5 ps (rms) and also to correct the nonlinearities of the longitudinal phase space.

(b) The bunch is accelerated through the linac a second time 55° after crest to a final energy of 469 MeV. Note that the rms relative energy spread is reduced from 0.84% to 0.28%.

Figure 6
(a) The bunch is accelerated on-crest through the afterburner to the final energy of 1.5 GeV.

(b) After the final compressor the bunch produces a peak current of 1.1 kA with a relative energy spread of 0.09% (rms).

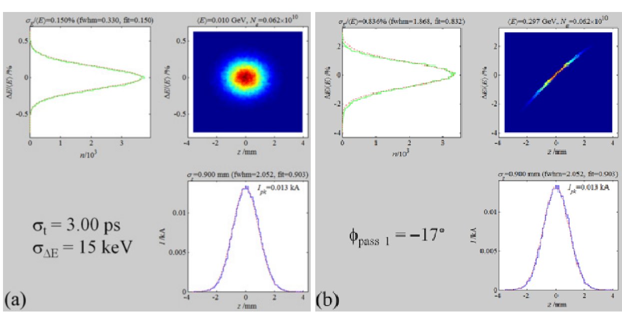

Figure 4: (a) Injected bunch at 10 MeV (b) Exit of the first pass through the linac.

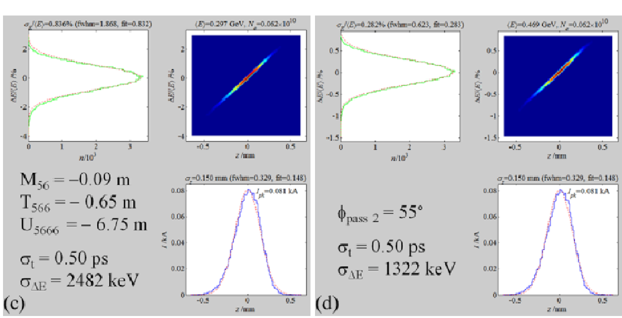

Figure 5: (a) Exit of the recirculator (b) Exit from second pass through linac.

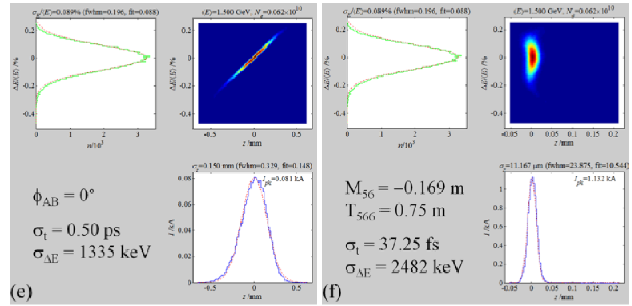

Figure 6: (a) Exit of afterburner (b) Exit of final bunch compressor.

SUMMARY AND OUTLOOK

A new longitudinal match has been presented which is appropriate for linac driven light sources, particularly continuous-wave (cw) sources. The scheme offers the potential to both reduce risk and cost of future machines. A proof-of-principle simulation has been done, however a full 6D phase space (longitudinal and transverse) machine design is required to fully assess performance.

It is interesting to note that the optimal energy gain for the recirculator is around 300 MeV (see Fig. 3). The Jefferson Laboratory FEL Upgrade Driver consists of 3 cryomodules which, if replaced with high gradient modules, could provide the 300 MeV energy gain necessary. It is also true that a notional recirculator design for 300 MeV has been designed for the extant JLAMP project [4]. Due to site limitations, the design would differ slightly from the schematic presented in Fig. 2 by adding a 180° arc after the recirculator to redirect the beam to the afterburner – which would run parallel to the linac in the recirculator. Maintaining beam brightness through 540° of bending presents a formidable challenge, yet such a design would allow a compact design for a 1.5 GeV soft x-ray source to fit on-site and leverage the available infrastructure of the FEL.

ACKNOWLEDGEMENTS

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