MULTI-BEAM INJECTION AND QUASI-CW ERL FOR FUTURE X-RAY LIGHT SOURCES*

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Abstract

The envisioned energy-recovery linac (ERL)-based x-ray light sources demand costly cw superconducting linacs and high-brightness high-average-current photoinjectors that are beyond the state of the art. To overcome the fiscal obstacle of a multi-GeV cw ERL and the physical challenge of photoinjectors, we explore a new scheme using multi-beam injection into a quasi-cw ERL. Multi-beam injection lowers the burden on individual rf injectors at subharmonics of the linac frequency. Low-frequency rf injectors allow higher bunch charge, which enables lower duty factor of the linac with significant reduction in construction and operation costs. Preliminary studies foresee many benefits and no obvious physical showstoppers, despite potential complexity.

INTRODUCTION

Foreseeable high-brightness photoinjectors promise much lower beam emittance and shorter bunch length than those normally achievable in conventional electron storage rings. An energy-recovery linac (ERL) can efficiently accelerate high-average-current beam to many GeVs, with little degradation of beam quality, by recouping most of the energy in a spent beam. Thus, ERL-based light sources promise much higher performance than state-of-art 3rd-generation light sources such as the Advanced Photon Source (APS). Although apparently feasible, ERL-based light sources face some significant challenges, especially for those envisioned multi-GeV, next-generation x-ray SR sources [1, 2]. This paper addresses physical challenges from photoinjectors and fiscal constraints from multi-GeV cw linacs. These are the major obstacles unveiled [2] when an ERL-based upgrade path was explored for the APS whose typical beam parameters are: beam current of 100 mA, normalized transverse emittances of 40 μm horizontal and 0.3 μm vertical, bunch length 40 ps, and relative energy spread of 0.1%. The envisioned ERL x-ray source has 0.3 (0.08)-μm emittance in both planes for the high-flux (high-coherence) mode with 100 (25)-mA average current, 2-ps bunch length, and 0.02% energy spread [3, 2].

QUASI-CW ERL FOR LIGHT SOURCES

Envisioned ERL x-ray sources rely on cw linacs to accelerate electron beam to the multi-GeV level for synchrotron radiation production. Even though energy-recovery linacs are very efficient for recovering beam power, multi-GeV cw linacs are very costly to build and operate, largely due to ohmic heat loss of rf power in accelerating structures, even with superconducting linacs. To understand the cost drivers of a multi-GeV ERL, we start with a simplified model [4, 5]:

$$\text{Cost} \sim C_L \frac{E}{E_a} + C_p \left(\frac{1}{\eta_\text{c}} + \frac{Q_0}{4Q_\text{L}\eta_\text{k}} \right) \frac{D\,E\,E_a R_s}{G(r_\text{sh}/Q_0)} + C_p \frac{I \Delta E}{\eta_\text{k}}, \quad (1)$$

where E is the linac energy; ΔE is the unrecovered energy; I is average beam current; E_a is the average accelerating gradient; C_L is the average capital cost per meter of the linac; C_p is the power cost per watt over expected machine lifetime; η_c is cryogenic cooling efficiency for the rf heat load; η_k is the efficiency of the rf power source such as klystron or IOT; D is rf duty factor; R_s, G, r_sh, and Q_0 are, respectively, the surface resistance, geometry factor, average shunt impedance per meter, and quality factor of linac cavities; and Q_L is the loaded quality factor. This model contains both construction and operation costs. (There are significant omissions, such as the capital for a cryogenic plant that is proportional to the sum of the static and dynamic heat load of cavities, and the power cost for static heat load that is proportional to linac length. However, they will reinforce our arguments based on the simplified model, which is intended for basic understanding instead of detailed cost estimate.) The first term reflects the capital cost of linac construction and prefers a short linac with high accelerating gradient E_a, but in current proposals [1, 2] is limited to 20 MeV/m by cavity heat load instead of gradient capability. The second term reflects power cost due to required rf power and the dynamic heat load of cavities (assuming high-order rf modes are well damped), which is a major concern for multi-GeV cw ERLs and will be addressed below. The last term reflects the rf power cost of unrecovered beam energy. The key advantage of ERLs is to limit the third term by recovering most of the power in a spent beam via deceleration in the same linac. Without energy recovery, a 1-GeV and 100-mA beam will consume 100-MW of rf power. Current ERL designs aim to reduce ΔE to below 10 MeV and thus limit the third term to less than 1-MW rf power for a 100-mA beam, independent of the linac energy E.

The last factor in the second term of Eq. (1) gives the dynamic heat load— dissipated rf power on cavity walls due to the accelerating field. The denominator $G(r_{sh}/Q_0)$ is determined by the size and shape of a cavity, which increases linearly with frequency as cavity size decreases. For the well-known 1.3-GHz TESLA superconducting cavity [6], $G(r_{sh}/Q_0) \simeq 3 \times 10^5\,\Omega^2/m$. This number can

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be improved over a small range by cavity shape optimization, e.g., the optimized low-loss design gains about 20% over the TESLA design. The heat load is proportional to the field gradient E_a. Lower E_a reduces rf heating but increases the construction cost; thus it is impractical to use a very low gradient for a high-energy linac. The other critical factor is the surface resistance R_s. The niobium surface resistance $R_s = R_{\text{BCS}} + R_{\text{res}}$. Operating at 2K, R_{BCS} drops to 15 nΩ, about 6 orders of magnitude lower than that of a room-temperature copper cavity. Thus, a superconducting cavity can gain orders of magnitude in heat reduction over a copper cavity, even after taking into account a low cryogenic cooling efficiency of $\eta_c \sim 10^{-3}$ for maintaining 2K. It is possible to push for lower R_{BCS} by operating at lower temperature before R_{res} becomes significant, but is limited by the drop in cooling efficiency. The residual surface resistance R_{res} is sensitive to surface condition and cavity preparation. After decades of improvement, 3 nΩ appears to be the state of the art [6], which corresponds to a quality factor of $Q_0 = 10^{11}$. Although a single-cell cavity was reported to reach $Q_0 > 10^{11}$ at 25 MV/m years ago [7], the current state-of-the-art is about $Q_0 \simeq 10^{10}$ for multi-cell cavities required in main linacs. It is important to pursue R&D for improving the quality factor, but in the near future, it seems difficult to significantly cut rf heating by reducing surface resistance.

The last and most effective controlling factor is the rf duty factor. In fact, high-energy linacs rely on operating at very low duty factors to limit rf heating. For example, the 250-GeV linac in the proposed International Linear Collider (ILC) has $D = 0.5\%$. For a multi-GeV superconducting linac needed for x-ray light sources, a much higher duty factor is possible for ERLs, but cw operation with $D = 1$ is still fiscally challenging for the time being. For example, the heat load would be around 15 kW for a 7-GeV linac using 20-MV/m cavities with 30-nΩ surface resistance, which requires at least 15-MW power just for cryogenic cooling. The natural question is whether quasi-cw operation, say $D = 0.25$, can provide a feasible route for mitigating the heat load obstacle to an ERL x-ray light source. The answer seems to be negative at first sight, because it will require $1/D$ times higher bunch charges in order to maintain the same average current. But, due to space charge, photoinjectors have already been stretched to provide the required ultralow emittance beam at a bunch charge for cw operation. Significantly higher bunch charges appear unlikely for now unless one uses longer bunches in low-frequency photoinjectors. These analyses lead to the idea of merging multiple beams from identical subharmonic photoinjectors into a quasi-cw linac. The next section presents a schematic design to accomplish this new scheme.

MULTI-BEAM INJECTION SCHEME

The basic idea is to produce higher charge and/or lower emittance bunches by significantly increasing the cathode field (comparing to DC gun) and the bunch length (comparing to rf gun at linac frequency) in rf photoinjectors at a subharmonic of the linac frequency, and then merge beams from multiple injectors into the linac. For convenience we describe the key merging technique backwards. Consider two bunches in a 1.3-GHz linac: they have the same transverse coordinates and the same energy, but are separated by one rf wavelength. To separate them spatially, we first introduce a significant energy difference (e.g., 5%) between the two bunches by accelerating one and decelerating the other in a subharmonic cavity of 650 MHz, as shown in Fig. 1. Then we pass the bunches through a bending system to separate them spatially. To preserve beam emittance, each beam must pass through a nondispersive (achromatic) optics. In other words, the system needs to be dispersive for large energy separation but nondispersive for small energy deviations within a bunch. Figure 2 illustrates a simple optics for accomplishing this task, using two achromats that share one bending magnet. One achromat uses a common 3-dipole design (similar to the Cornell ERL merger design [1], but with weaker focusing in the middle dipole), and the other uses a 4-dipole zigzag design [8], where a static

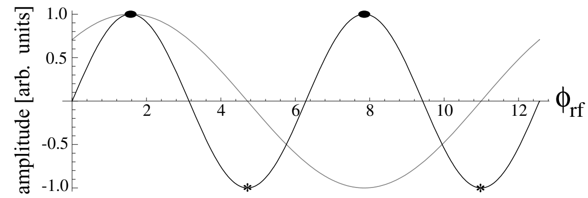

Figure 1: Two bunches (large dots) from two cycles of the main linac wave (black) are synchronized with a subharmonic wave (gray) to accelerate the first bunch and decelerate the second. A few-percent energy separation can be gained in a single-cell subharmonic cavity. Off-crest operation is possible. Energy-recovery bunches (stars) can also pass the subharmonic cavity at the zero crossings for merging three beams. There is little beam loading in the subharmonic cavity.

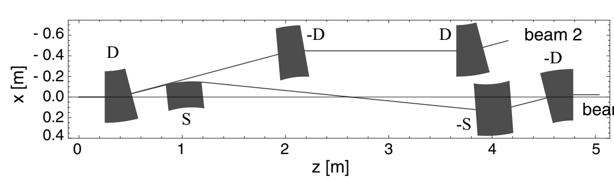

Figure 2: Schematic of a two-beam merger. Going backward, two bunches with 5% energy separation are bent by a 15° dipole (D) into slightly different directions. The high-energy bunch is deflected by a static dipole septum (S) and then passes through a zigzag achromat formed with two opposite dipoles (-S and -D). The low-energy bunch passes through a 3-dipole achromat. With some effort, it may be possible to merge the energy-recovery beam at the same time (not shown).

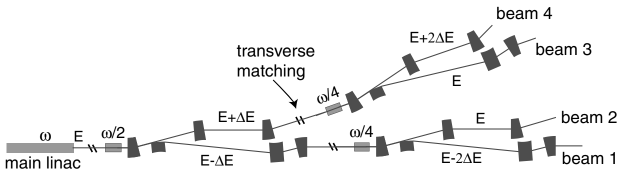

Figure 3: Schematic of a 4-beam merger by staging three 2-beam mergers (the high-energy beam is not shown). The subharmonic frequencies and beam energies are indicated. No pulsed devices (magnetic or rf kickers) are used in the merger to preserve beam emittance.

septum magnet is used as the second dipole to separate the two beams onto different paths. Beam separation Δx at the septum entrance is a critical parameter given by

$$\Delta x = \left(2\rho \sin^2 \frac{\phi}{2} + L \sin\phi\right) \delta, \qquad (2)$$

where ρ, ϕ, L, and δ are the bending radius, bending angle, drift length to the septum, and relative energy separation, respectively. In Fig. 2, with $\rho = 1$ m, $\phi = 15°$, and $L = 0.35$ m, there is about 6.3-mm clearance between the two beams with 5% energy separation, sufficiently large to use a septum, especially considering the small beam size due to the ultra-low emittance and energy spread from the photoinjectors. To better preserve beam emittance through the achromats, all-dipole designs with small bending angles typical for ERL mergers are used. The zigzag achromat may mitigate the detrimental space-charge effect (as well as CSR effect), but the dogleg may or may not [8]. So, in the worst-case scenario, such a merger can be used at relatively high beam energy, say 30 MeV, where the space-charge force ($\propto 1/E^2$) is sufficiently weak. Unfortunately, this worst-case scenario will raise the unrecovered beam power, the last term in Eq. (1), from 1 to 3 MW for a 100-mA beam. In a facility design, the merge energy must be carefully optimized to lower unrecovered power. However, the idea here is that a large reduction of linac power consumption from quasi-cw operation will dwarf the extra unrecovered beam power (which, in fact, may be recovered with extra effort).

Two-beam injection can already provide potential benefits larger than most of the other options. It is even more effective (at the cost of increased complexity) to cascade 2-beam mergers to accommodate four beams, as sketched in Fig. 3. The synchronization of the subharmonic rf waves are shown in Fig. 4. Three short subharmonic cavities are needed (one at frequency $\omega/2$ and two at $\omega/4$ in the second stages), together with three 2-beam mergers. Maximum beam energy separation is about 10%. Matching of transverse Twiss parameters are necessary, but straightforward. It might be possible to design a 4-beam merger using one $\omega/4$ subharmonic cavity, but large off-crest acceleration/deceleration has to be used with each bunch on a different rf slope. Furthermore, it will be difficult to accommodate four achromats all together in one stage.

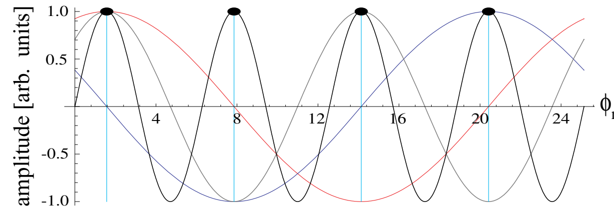

Figure 4: Synchronization of four cavity waves to introduce the required energy separation in adjacent four bunches. Black curve is the main linac wave of frequency ω. Gray wave separates bunches 1 and 3 from bunches 2 and 4 at frequency $\omega/2$. Red (blue) wave further separates bunch 1 (2) from 3 (4) at frequency $\omega/4$.

REMARKS

It appears straightforward in principle to implement multi-beam injection. Although the most critical, photoinjectors are a relatively inexpensive component in multi-GeV light sources. The required septum field strength is given by $B = E[\text{GeV}]/0.3\rho[\text{m}] = 0.1$ T even for a 30-MeV beam and 1-m bending radius, which is not too high to use a static septum necessary for avoiding jitters. The subharmonic cavity can operate at low gradient, around 1 MV/m. This short paper can not address many feasibility concerns such as multi-beam synchronization, jitters, beam breakup in the ERL linac, and transit effects due to pulsed operation. Suffice to say, preliminary considerations foresee many extra benefits without obvious showstoppers [9]. The proposed scheme relies on higher bunch charge from low-frequency rf guns (than cw DC guns). A simulation study of such an injector at 325 MHz is given in [10].

REFERENCES

[1] S.M. Gruner & M. Tigner, eds., CHESS Technical Memo 01-003/JLAB-ACT-01-04 (2001).

[2] M. Borland, G. Decker, A. Nassiri, M. White, Proceedings of PAC07, p. 1121 (2007).

[3] G. Hoffstaetter, "Status of the Cornell ERL Project," FLS 2006 workshop.

[4] T.P. Wangler, *Principles of RF Linear Accelerators*, Wiley & Sons, Inc. 1998.

[5] H. Padamsee, J. Knobloch, and T. Hays, *RF Superconductivity for Accelerators*, Wiley & Sons, Inc. 1998.

[6] B. Aune et al., Phys. Rev. ST Accel. Beams **3**, 092001 (2000).

[7] H. Safa, *Proceedings of the 10th Workshop on RF Superconductivity*, Tsukuba, Japan, p. 279 (2001).

[8] V.N. Litvinenko, R. Hajima, and D. Kayran, Nucl. Instrum. and Methods. A**557**, 335 (2006).

[9] C.-x. Wang, "A scheme to realize energy-recovery-linac based next-generation x-ray light sources," Advanced Photon Source internal note ASD/APG/2008-09 (2008).

[10] C.-x. Wang, "Simulation study of normal-conducting rf photoinjectors for ERL x-ray sources," in these Proceedings.