A METHOD OF EMITTANCE PRESERVATION IN ERL MERGING SYSTEM*

D. Kayran[#], V.N. Litvinenko, BNL, Upton, NY 11973, U.S.A..

Abstract

Energy recovery linacs (ERLs) are potential candidates for the high power and high brightness electron beams sources. The main advantages of ERL are that electron beam is generated at relatively low energy, injected and accelerated to the operational energy in a linac, and after the use is decelerated in the same linac down to injection energy, and, finally, dumped. A merging system, i.e. a system merging together high energy and low energy beams, is an intrinsic part of any ERL loop. One of the challenges for generating high charge, high brightness electron beams in an ERL is development of a merging system, which provides achromatic condition for space charge dominated beam and which is compatible with the emittance compensation scheme. In this paper we present the principles of operation and some designs (including simulations) of such merging systems. We use a specific implementation for R&D ERL at Brookhaven as the illustration.

INTRODUCTION

ERL is emerging accelerator technology, which promises to become a major driver for accelerator application requiring the high current and high brightness electron beams. The main advantages of ERL are that a fresh electron beam is generated at relatively low energy, injected and accelerated to the operational energy in a linac, and after a single use is decelerated in the same linac to injection energy, and is deposed of after taking its energy back.

This feature of ERL makes it especially attractive for the processes, which significantly affect quality of electron beam at a single pass, such as a significant energy spread growth in an FEL [1] or a significant increase of the transverse emittance in an interaction point (IP) of a collider [2]. Similarly, ERLs promise to maintain high average and peak brightness of electron beams during acceleration and the use in future synchrotron radiation sources [3]. Higher brightness of these light sources will be achieved by limiting the affects of quantum fluctuations of spontaneous radiation on the energy spread and emittance growth to a few turns compared with continuous affect in storage rings. ERL also promise to bring to life X-ray sources with sub-picosecond durations.

A generic one-loop ERL is shown in Fig. 1. It has a gun system, a merger, a linac, a loop and, finally, a dump. In all cases, an ERL should preserve the high brightness electron beams generated at the gun through the entire process of acceleration, merging and transportation to the place of the use. Only after the use the preservation of beam quality becomes less important, unless it affects the energy recovery and lossless transportation to the dump.

ERL should operate with ampere-class beam currents to be competitive with storage rings. It translates into CW electron beams with average power from hundreds of megawatts to tens of gigawatts. Only low injection energy and very high efficiency energy recovery in superconducting RF (SRF) linacs makes the such ERL economically feasible. Furthermore, the use of low injection and ejection energies mitigates the radiation and environmental issues related to a dumping of megawatt class electron beam. Using electron energy well below 10 MeV dramatically reduces nuclei activation of the beam dump material which otherwise may become a major environmental and cost problem.

A merging system, i.e. a system merging together high energy and low energy beams, is an intrinsic part of any ERL loop located between the gun (which is desirably generates low emittance high quality electron bunches) and the main linac. It means that low energy electron, affected by space charge fields, will propagate through the merger before being accelerated to high energy where space charge effects are suppressed.

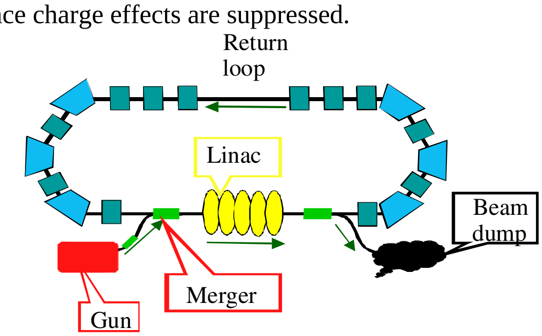

Figure 1: Schematics view of ERL: electron beam is generated in the gun passes through a merger section, is accelerated to high energy, used and then is decelerated and dumped.

Ways of combating the emittance growth in high brightness electron accelerators is well understood both theoretically [4] and experimentally [5]. This method, called emittance compensation, was developed for systems with axial symmetry. Any merger is using at least one dipole magnet, which both breaks the axial symmetry and strongly couples longitudinal and transverse (that in the plane of the bending) degrees of freedom. Hence, the traditional method of emittance compensation is no longer directly applicable to the merger system.

One of the challenges for generating high charge, high brightness electron beams in an ERL is development of a merging system, which provides achromatic condition for

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[#]dkayran@bnl.gov

space charge dominated beam and which is compatible with the emittance compensation scheme.

MERGER DESIGN FOR LOW EMITTANCE ERL

In the absence of space charge forces, the coupling between longitudinal and transverse degrees of freedom is cancelled by the use of an achromatic lattice for a merger – i.e. a magnetic system where transverse position of the particles at its exist does not depend on particles energy. The design of such achromatic system assumes that energy of the particles remains constant while they propagate through the system.

At present time there are three operational ERLs at Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia [6], at Tomas Jefferson National Accelerator Facility (TJNAF), Newport News, VA, USA [7] and at Japan Atomic Energy Research Institute (JAERI), Tokai-mura, Ibaraki, Japan [8].

The summary of beam parameters for this operation ERLs which are using different types of merger system is presented in Tab.1

Table: 1. Beam parameters after the mergers in operation ERLs

	BINP [6]	TJNAF [7]	JAERI [8]
Gun type	Thermionic	Photocathode	Thermionic
Inj.energy	2 MeV	9.1 MeV	2.5 MeV
Q_{bunch}	1.5 nC	0.135 nC	0.5 nC
ΔT_{bunch},	150 psec	2 psec	9.4 psec
Merger type	Chicane with quads strong focusing	Three dipole strong focusing	Dog-leg, with quads strong focusing
$\varepsilon_{N\_x}/\varepsilon_{N\_x}$	30/30 μ	10/10 μ	35/26 μ

As we see all existing ERLs operate with electron beam emittances 10-to-30 times larger compared with those generated by best linac photo-injectors [5,13]. At the same time most of the future ERL projects plan to use very low beam emittances comparable or even better than those achieved in the best linac photo-injectors [2,3,9].

In contrast with the ERLs, the low-emittance linacs are based on emittance compensations scheme utilizing axial symmetric elements till the end of the main linac, i.e. there is no dipoles or mergers or any kind seen by low energy beam.

In order to attain low beam emittance operation in ERLs it is essential to combine a merger, which decouples the longitudinal and transverse degrees of freedom, with emittance compensation schemes. One of very important requirements for emittance compensation scheme to work is that the motion of the electron in the section remains laminar (i.e. electron trajectories do not cross) [4]. There are two effects which are important for design of a merger for space charge dominate e-beam:

- the space charge de-focusing must be taken into account in the design of the achromatic merger. Defocusing caused by space charge can modify significantly the achromatic conditions;
- lattice of the merger must be designed with the use of only weakly focusing elements with focal lengths larger or of the order of the merger length.

If one of these conditions is not satisfied, the space charge causes significant emittance growth in a merger, often irreversible by practical means (see [4,11] for details).

Natural way of designing a merger for a low emittance ERL should include a dipole scheme, which provide for these conditions by its geometry, i.e. without use of any strong focusing elements. One of such system is described below.

ZIGZAG MERGER

The idea of Zigzag merger [9-11] came from a simple observation of the energy variation in space charge dominated electron beam from 1.5 cell SRF gun studied for BNL's ERL [10,11] using PARMELA*) [14]. Our studies did show that for a large number of cases we can use following approximate formulae for particles energy:

$$\delta(s) \cong \delta_o + f(\zeta_o)\cdot(s+\alpha\cdot s^2) \qquad (1)$$

where functional dependence on the initial longitudinal position in the bunch, ζ_o.

A typical s-dependent energy variation is very close to linear i.e. as in so-called frozen case. To satisfied achromatic conditions in case of linear changes of energy we should make zero four integrals

$$\int_{s_o}^{s_f} K_o(s)\cdot m_{12}(s|s_f)\cdot ds = 0; \qquad (2a)$$

$$\int_{s_o}^{s_f} K_o(s)\cdot m_{11}(s|s_f)\cdot ds = 0;$$

$$\int_{s_o}^{s_f} K_o(s)\cdot s\cdot m_{12}(s|s_f)\cdot ds = 0; \qquad (2b)$$

$$\int_{s_o}^{s_f} K_o(s)\cdot s\cdot m_{11}(s|s_f)\cdot ds = 0;$$

where $K_0(s)$ is curvature of trajectory, $m_{12}(s|s_1)$, $m_{11}(s|s_1)$ are elements of transport matrix from s to s_1 (more details are given in [10, 11]). The studies of emittance growth caused by longitudinal space charge force were also considered by *R. Hajima et al.* using first-order beam transport approach[12].

One of general approaches for developing merger lattices satisfying these conditions can be the using of lattice symmetries.

As an oversimplified example of a Zigzag merger system consists of 2K short dipoles (with bending angle

*) PARMELA is quite an approximate code for example it does not include coherent synchrotron radiation effects and self consistent wake fields.

θ_k and position s_k each Fig. 2) without focusing in horizontal direction. In this case the elements of transport matrix are: $m_{11}=1$, $m_{12}=s$ and only one condition remains to be satisfied:

$$\sum_{k=1}^{K} s_k \cdot \theta_k = 0 \qquad (3).$$

For K=2 (a four dipoles Zigzag) the condition (3) gives a simplest Zigzag with $s_2=2s_1$, $\theta_1=-2\theta_2$.

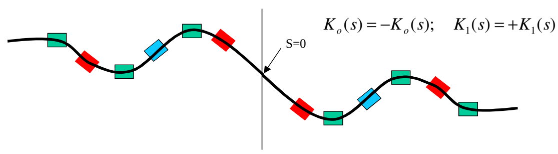

Figure 2: Schematic of a Zigzag based on the symmetry: green boxes are the dipoles, red and blue boxes are focusing and defocusing lenses.

Our simulation tests demonstrated that this simple concept of Zigzag combined with optics typical for emittance compensation schemes (i.e. a couple of solenoids located between the gun and the main linac in axially symmetric system, see Fig. 3) provided for almost ideal preservation of emittances both in and out of the bending planes for magnets with small bending angles. To our surprise this simple concept, some version of which were intuitively used previously , works very well for many processes, including coherent synchrotron radiation [15].

Increase of the bending angles causes additional focusing, which should be almost evenly distributed between horizontal and vertical directions using edge focusing (so-called chevron magnets), and the strength of solenoidal focusing should be adjusted in order to preserve the emittance compensation mechanism. Furthermore, the geometry of the Zigzag should be slightly adjusted (i.e. the angles and distances between the magnets, see [10-11]) to take into account the focusing from the dipole magnets and the defocusing from the beam space charge forces in the matrix elements and to satisfy the decoupling conditions (2).

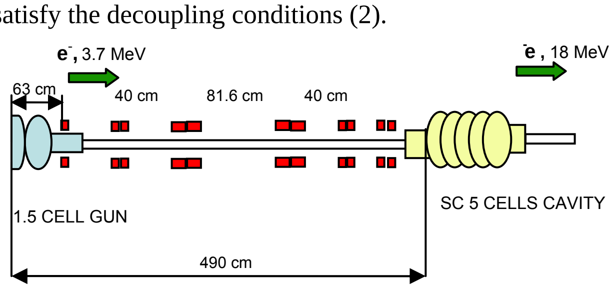

Figure 3: A schematic geometry system with axial symmetry comprising of a 1.5 cell 3.7 MeV electron SC 703.75 MHz RF gun and 5-cell SC 703.75 MHz RF linac with emittance compensation solenoids between them.

In order to compare performance of Zigzag with axially symmetric scheme (without a merger) and with another merger schemes we developed a following test, illustrated in Fig. 4, by adding dipole magnets into the scheme shown in Fig. 3 to form achromatic mergers in form of a Zigzag, a chicane and a "Dog-leg", while keeping the length of the path the same. All configurations are achromatic for particle with constant energy, i.e. in the conventional sense that regular dispersion is compensated (2a). In the Zigzag this condition was satisfied by a slight increase of the center straight section to 81.6 cm from 80 cm. In the chicane it was reached by modification of the angles. And in the dog-leg the achromaticity was achieved by introducing two couple short focusing solenoids to make a minus unit matrix.

To make a fair comparison, all systems have the same focusing strength and are made of chevron dipoles with 86 cm radii or curvature. The strength of the solenoids was adjusted for the best emittance compensations in all cases.

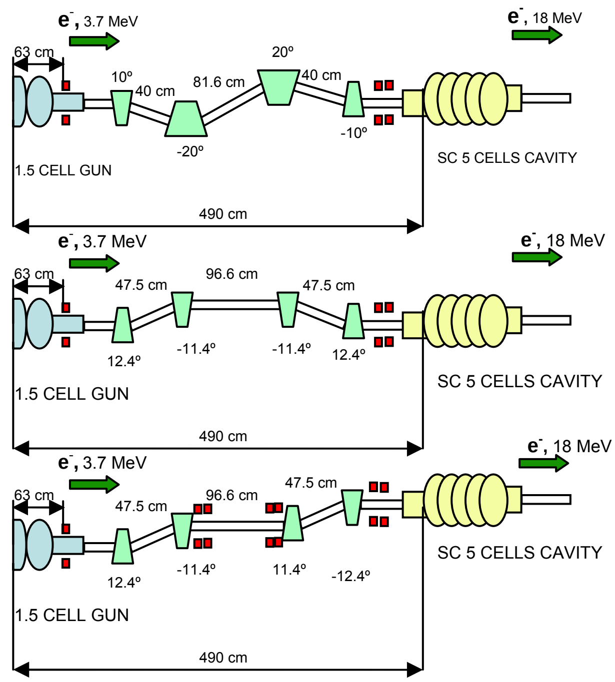

Figure 4: Three mergers schemes (from trop to bottom: the Zigzag, the chicane and the Dog-leg) installed into the emittance compensations system, shown in Fig. 2

In the numerical test performed with PARMELA, a 1 nC electron bunch from the 1.5-cell RF gun was propagated through the above systems followed by a 15 MeV 703.75 MHz linac. The kinetic energy of electron beam at the gun exit was 3.7 MeV. Initial beam has "beer-can distribution" with duration of 12° and radius 4 mm at the cathode of the gun. Comparison of the emittance evolution in the system is shown in Fig. 5. In two merging systems (the chicane and the Zigzag), vertical emittance evolution is very similar to that of the axially symmetric system with final value of about 1.4 mm·mrad (normalized). In the chicane horizontal emittance remain very large (~ 5 mm·mrad, normalized) after the merger and main linac. Detailed study shows that this is direct result of energy variation along the path and the violation of the decoupling condition (2b) for this case.

At the exit of the Zigzag merger, horizontal emittance is practically identical to the vertical and reaches 1.4 mm·mrad (normalized) at the end of the system, i.e. when the emittance compensation process is completed. Hence, in this case the Zigzag provided both for the decoupling conditions (2) and for emittance compensation.

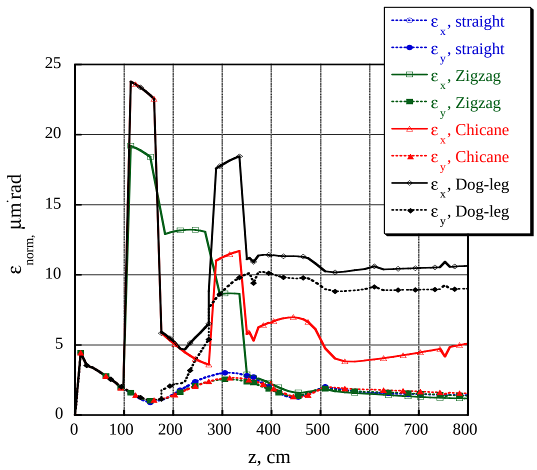

Figure 5: Evolution of horizontal and vertical normalized emittances in the four systems: the axially symmetric system, the Zigzag, the chicane and the Dog-leg.

In contrast with both the chicane and the Zigzag, the Dog-leg merger causes significant increases in both horizontal and vertical emittance. Even though the Dog-legs formally satisfies the decoupling conditions (2) for a low charge beams, it violates the laminar conditions via use of a strong focusing elements necessary for achromaticity of this system.

Further studies of the Zigzag merger showed that it preserves its qualities (i.e. equal emittances and compatibility with emittance compensation schemes) for a wide range of the beam parameters (charges from 0.1 nC to 10 nC per bunch, energies as low as 2.5 MeV in the merger, energy spread of ±10% in the e-beam, etc.).

CONCLUSIONS

Merger is one distinct element of any ERL, which makes it different from standard axially-symmetric low emittance linear accelerators. Desire to operate electron beams with significant charges per bunch and to lower energy of injection into ERL requires mergers compatible with emittance compensation in space-charge dominated beams. In addition, variation of particles energies along the pass of a merger, caused by the space charge forces of the bunch, introduce additional conditions on the merger lattice.

Mergers used in presently operating ERLs were not designed for operating with very low emittance electron beam, and , therefore, can not be used for ERL operating beams with normalized emittances ~ 1 mm mrad or lower.

We introduced a physics model which provides for decoupling of transverse and longitudinal degrees of freedom for space charge dominated beams in ERL's mergers. We tested this model using PARMELA simulations and had found that PARMELA results support the model. The simulations were done for very long bunches with very low peak current, where effects of coherent synchrotron radiation are not dominant however there are indications [15] that zigzag-like system also helps to mitigate CSR (coherent synchrotron radiation) effects. Further simulations using various electrodynamics codes and, ultimately, experiments are needed for confirmation of this approach as well for indicating the range of its applicability. The experimental validity of the Zigzag merger and its performance in ERL will be tested in 20 MeV, 0.5 A ERL which is under construction as Brookhaven national Laboratory [9].

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