BROOKHAVEN
NATIONAL LABORATORY

BNL-77347-2007-CP

Merger System Optimization in BNL's High Current R&D ERL

D. Kayran, V.N. Litvinenko, BNL, USA

Presented at the 22nd Particle Accelerator Conference
Albuquerque, NM
June 25-29, 2007

June 2007

Collider-Accelerator Department

Brookhaven National Laboratory
P.O. Box 5000
Upton, NY 11973-5000
www.bnl.gov

DISCLAIMER

MERGER SYSTEM OPTIMIZATION IN BNL'S HIGH CURRENT R&D ERL*

Dmitry Kayran and Vladimir N. Litvinenko
Brookhaven National Laboratory, Upton, NY, USA

Abstract

A super-conducting RF R&D Energy recovery linac (ERL) is under construction at Brookhaven National Laboratory (BNL). This ERL will be used as a test facility to study issues relevant to high-current, high-brightness beams. One of the goals is to demonstrate an electron beam with high charge per bunch (~ 5 nC) and extremely low normalized emittance (~ 5 mm-mrad) at an energy of 20 MeV. In contrast with operational high-brightness linear electron accelerators, all presently operating ERLs have order of magnitude larger emittances for the same charge per bunch. One reason for this emittance growth is that the merger system mixes transverse and longitudinal degrees of freedom, and consequently violates emittance compensation conditions. A merger system based on zigzag scheme [1] resolves this problem. In this paper we discuss performance of the present design of the BNL R&D ERL injector with a zigzag merger.

INTRODACTION

The R&D ERL facility at BNL aims to demonstrate CW operation of ERL with average beam current in the range of 0.1-1 ampere, combined with very high efficiency of energy recovery [2].

Two operating modes are envisaged, namely the high current mode and the high charge mode. The high current (0.5 A) mode will operate electron bunches with lower normalized emittance, 0.7 nC charge per bunch at 703 MHz rep-rate. In this case, the full energy of electrons at gun exit is limited by the available RF power 2.5 MeV. In high charge mode electron beam will consist of bunches with charge up to 5nC per bunch at 10MHz repetition rate, 50 mA average current. The electrons energy at the exit of the gun can be pushed upto 3.0-3.5 MeV by the maximum field attainable in the super-conducting gun itself.

The ERL design (shown in Fig. 1) has one turn: electrons are generated in the superconducting half-cell gun and injected into the main superconductive linac. Linac accelerates electrons 15-20 MeV, which pass through a one turn re-circulating loop with achromatic flexible optics [3].

The photocathode is located in a high electric field for immediate acceleration of the electrons to as high energy as possible, reducing emittance degradation due to strong space charge force. Furthermore, liner part of space charge effects is compensated by applying a suitable external solenoid magnetic field.

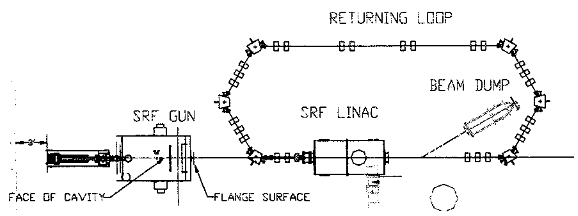

Figure1: Layout of the BNL R&D energy recovery linac.

In nominal recovery operation regime the path-length of the loop provides for 180 degrees change of the RF phase, causing electron deceleration (hence energy recovery) down to injection energy. The decelerated beam separates from the higher energy beam and goes to the beam-dump.

LAYOUT OF THE BNL R&D ERL INJECTOR

The electron injector is a central part of any ERL that has to deliver high brightness electron beam. The BNL R&D ERL injector (see Fig. 2) consist of ½ cell superconducting RF gun with photocathode inside, solenoid, four dipoles and two solenoids turned on in opposite direction (in order to match the electron beam with linac entrance more accurately). The 4th dipole mergers the high and low energy beams.

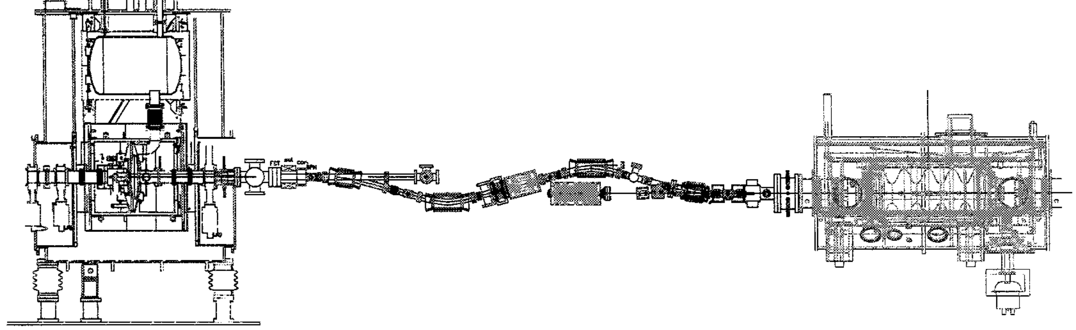

Figure 2: Detailed drawing of SRF Injector for the BNL R&D ERL.

*Work performed under the auspices of the U.S. DOEContract No. DE-AC02-98CH10886 and partially funded by the US DOD
#dkayran@bnl.gov

SRF Gun

The first important component of the injector, which determines the attainable parameters of the electron beam, is the gun. For R&D ERL the superconducting 703.75 MHz RF (SRF) gun was selected (Fig.3). The gun design with a short 8.5 cm cell was chosen in order to provide reasonably high electric field at the cathode at this low accelerating voltage. To provide effective damping of high order mode (HOM) this gun has rather large iris radius of 5 cm. More details on the SRF gun and its photocathode system can be found elsewhere [4].

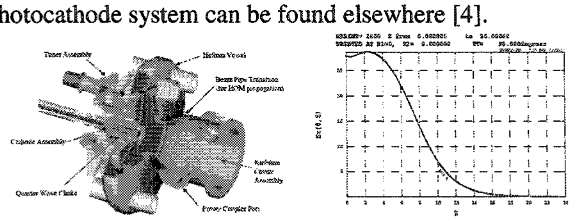

Figure 3: SC RF Gun shape and electric field on the axis (results of the SUPERFISH [5] simulation).

Merger system

One of the critical parts of the ERL injectior is the merger of the low energy- and high energy beams (Fig. 4). The injection energy is not recovered. Low injection energy requires less RF power and lowers dumped beam energy. The original emittance compensation scheme [6] does not include any dipoles between RF gun and linac (or booster cavity).

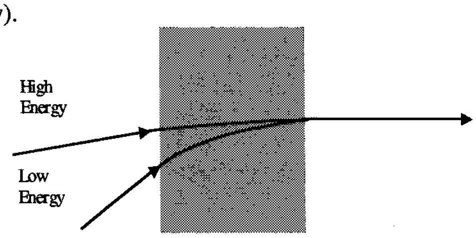

Figure 4: Main function of a merger – combining two (or more) beams with different energies.

Focusing of the bending magnets in the merging section has significant effect on the low energy electrons. Different focusing in vertical and horizontal planes (astigmatism) makes impossible simultaneous emittance compensation. Hence, the use of combined function magnets with equal focusing strength in x- and y-direction is necessary [7]. The merger must be designed to minimize degradation of the low energy beam emittance.

Any dipole magnet excites the coupling between energy and transverse motion which leads to effective correlated emittance growth:

$$\varepsilon_x^{eff} = \sqrt{\varepsilon_x^{\,2} + \sigma_x^2 D'^2 \sigma_\delta^2 + \sigma_{x'}^2 D^2 \sigma_\delta^2}\,,$$

where: D-is dispersion, D' -is dispersion derivative, ε_x is emittance without dispersion and $\sigma_x, \sigma_{x'}, \sigma_\delta$ are rms size, angular spread and energy spread respectively.

The full merging system has to decouple such correlations at the exit (i.e. full decupling of longitudinal and transverse motions). There are many systems which work very well in the absence of space charge effects: chicane, dogleg, achromatic bend etc.

Basically it means that the achromatic system has to satisfy two traditional conditions:

$$\int_{s_o}^{s_f} K_o(s)\cdot m_{12}(s|s_f)\cdot ds = 0; \int_{s_o}^{s_f} K_o(s)\cdot m_{22}(s|s_f)\cdot ds = 0,$$

where $K_0(s)$-is curvature of trajectory, s_0, s, s_f - are initial, current and final positions respectively along the transport system $m_{12}(s|s_f)$, $m_{22}(s|s_f)$ – are (1-2) and (2-2) elements of 6x6 transport matrix from s to s_f position.

In presence of a space charge effect the particles energy is changing during the passing through the merger system. In this case to decouple transverse and longitudinal motions the additional two conditions have to be satisfied:

$$\int_{s_o}^{s_f} K_o(s)\cdot s\cdot m_{12}(s|s_f)\cdot ds = 0; \int_{s_o}^{s_f} K_o(s)\cdot s\cdot m_{22}(s|s_f)\cdot ds = 0.$$

One of the possible merging schemes which satisfied both pairs of conditions and preserves the emittance of the low energy is shown in Fig. 2. This Z-system provides a minimum set of elements (4 magnets) for the decopling. The detailed description of the Z-system, its principles of operation and comparison different merger systems can be found in [1]. Fig. 5 shows result of PARMELA [8] simulations of the ERL injector for different charge per bunch.

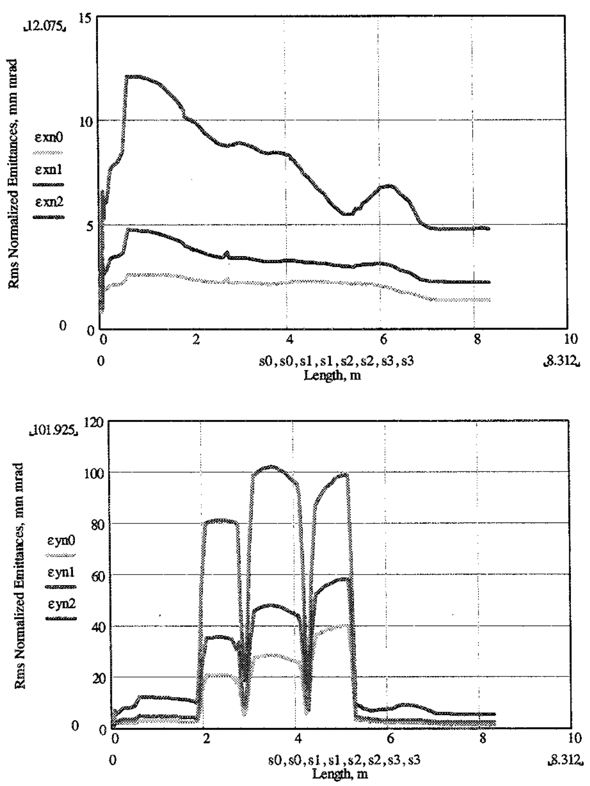

Figure 5: Evolution of normalized beam emittances (top figure – horizontal, bottom figure- vertical) in the ERL injector. Bunch charge: 0.7 nC-GREEN, 1.4 nC- RED, 5nC –BLUE.

Due to the bends in vertical direction the effect of vertical emittance growth is clear. But at the exit of Z-merger both: vertical and horizontal emittances become almost equal. In case of 5 nC per bunch this equality is broken, the next order nonlinearity start playing a role.

LONGITUDINAL BEAM DYNAMICS

Longitudinal motion is determined by the initial phase at the cathode, accelerating voltage and the space charge. Space charge increases a negative energy chirp from head to tail of the electron bunch and makes it longer. For the first year of Prototype ERL operation there is no plan to use any booster-chopper RF cavity in injection line. Only a natural slope of the energy gain versus the launch phase and ballistic compression can be used to prevent electron beam from lengthening. Fig. 6 shows the energy gain in the gun as a function of the initial phase of the electrons. Results of PARMELA simulation for energy spread and bunch length evolutions (0.7 nC per bunch) for two different initial phases are shown in Fig. 7.

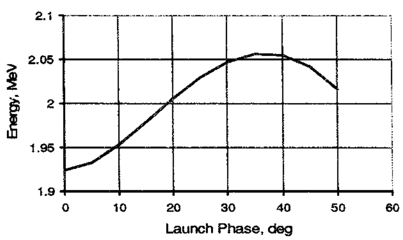

Figure 6: Electron beam energy gain at the exit of the gun versus initial phase

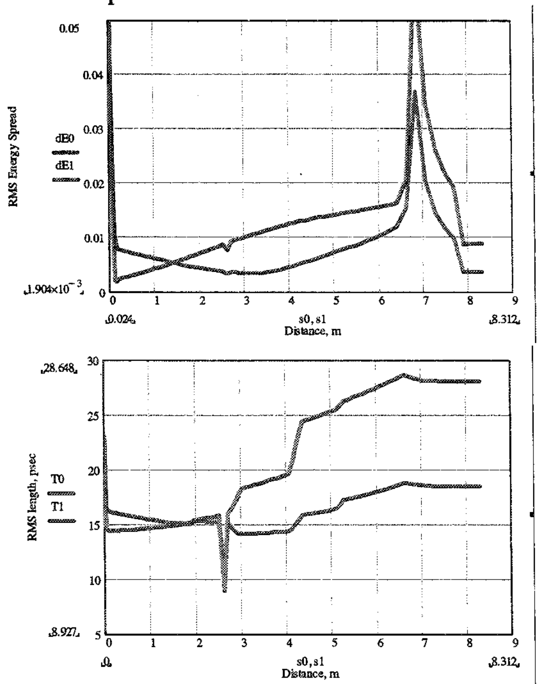

Figure 5: RMS energy spread (top figure) and rms bunch length (bottom figure) as a function of distance from the cathode for two different launch phases 25 deg - RED and 35 deg – BLUE

CONCLUSIONS

We have demonstrated a design of injector for BNL R&D ERL that can produce ampere electron beam with low emittance. High brightness injector will serve as a electron source for the prototype ERL. The results of the design studies of the R&D ERL and PARMELA simulation are very promising. The main expected electron beam parameters of this system are listed in Table 1.

Optimization of the transverse beam emittance and the longitudinal beam emittance for BNL R&D ERL injector results in different launch phases. We plan to use both modes of operation.

ACKNOWLEDGEMENTS

Authors would like to thank I. Ben-Zvi, R. Calaga, X. Chang, J. Kewisch and E. Pozdeyev for useful discussions.

Table 1: Electron beam parameters of the R&D ERL injector.

Charge per bunch, nC	0.7	1.4	5
Injection energy, MeV	2.5	2.5	3
Max. beam energy, MeV	20	20	20
Average beam current, A	0.5	0.5	0.05
Bunch rep-rate, MHz	700	350	9.4
Normalized emittance ex/ey, µm	1.4/1.4	2.2/2.3	4.8/5.3
Rms energy spread, %	0.35	0.5	0.97
Rms bunch length ps	18.5	21	31

REFERENCES

[1] V.N. Litvinenko, R. Hajima, and D.Kayran, Nucl. Instr. and Meth. A 557 (2006) 165.

[2] I. Ben-Zvi at al., "Extremely High Current, High-Brightness Energy Recovery Linac", PAC2005.

[3] D. Kayran et al, Optics for High Brightness and High Current ERL Project at BNL, PAC 2005, pp. 1775-1777.

[4] A. M. M. Todd et al., "State-of-the-Art Electron Guns and Injector Designs for Energy Recovery Linacs",.PAC2005, p. 2292.
Rama Calaga, Ph.D. Thesis Stony Brook University, 2006.

[5] James H. Billen and Lloyd M. Young, "SUPERFISH/Poisson Group Of Codes". Report LA-UR-96-1834, Los Alamos, 1996.

[6] J. B. Rosenzweig and L. Serafini, Phys. Rev. E 49, 1599 (1994)

[7] Wuzheng Meng et al., Unique features in magnet designs for R&D Energy Recovery Linac at BNL, these proceedings MOPAS097

[8] L. M. Young, J. H. Billen, "Parmela documentation", LA-UR-96-1835.