ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPA019

ACHROMATIC LOW ENERGY MERGER FOR ENERGY RECOVERY LINACS

M. Rossetti Conti*, A. Bacci, D. Giove, S. Samsam, D. Sertore and L. Serafini,
INFN - Sezione di Milano, Milano and LASA, Segrate (MI), Italy

Abstract

Nowadays, Energy Recovery Linacs (ERLs) became really appealing thanks to their low environmental impact and high sustainability. ERLs require a special low energy injector, usually named merger. The energy at merger exit is clearly the energy that can't be recycled in the ERL machine and is the amount dumped at the end. The lower the injection energy is the more efficient is the energy recovery process. A physiological issue of low energy ERL injection is the presence of space charge in the dispersive section that introduces dispersion leaks.

Worldwide ad hoc solutions for mergers beamlines design have been studied to address this problem.

Here we present a different approach that allowed us to exploit a standard dogleg to design a very low energy merger for an ERL. This has been made possible thanks to the application of the GIOTTO AI code that optimizes of the optics setting finding a proper achromatic configuration.

INTRODUCTION

In new accelerator machine worldwide projects that aim at very high average beam current the issue of the energy sustainability is becoming of increasingly important. Therefore, it is crucial to recover the beam energy after it has been used, instead of throwing it away into the dump. Further, to dump a beam that has a lot of stored energy is itself a problem. For example, in addition to the high fluxes of Bremsstrahlung x-ray radiation generated, it must be considered that electron beams of 8-10 MeV impacting metals turn on the neutron production, leading to further complications from the radiation protection point of view. Nowadays, many accelerators facility projects are beginning to consider ERLs as a solid solution [1]. This trend is largely attributable to the high energy-efficiency of these kinds of machines, which offer exceptional beam flux performance that was previously unachievable.

In essence, the operational scheme of an ERL is based on the injecting of a beam into an ultra-high Q (quality factor) linac at an initial energy of E_0, accelerating the beam to the energy level (E_{max}) needed for the specific application. Then, the beam is re-injected into the linac, in deceleration phase, to recover its energy. The process brings back the beam energy to the injection value E_0, after that the beam is dumped.

In order to minimize the wasted beam power:

$$P_{\text{dump}} = E_0 \cdot f \cdot \frac{Q_b}{e} \tag{1}$$

with Q_b/e the number of particles per bunch and f the rep.rate, it is straightforward that the energy E_0 should be as low as possible.

The drawback of a low-energy injection comes from space-charge (SC) effects which are dumped with a power that scales with $\frac{1}{(\beta\gamma)^3}$ and a complex emittance control [2].

With the objective to minimize P_{dump}, preserving the beam quality, in this proceeding is presented the study of a new ERL injector capable to work at the low energy of $E_0 = 4.5\,\text{MeV}$.

This new scheme employs a mild field DC-gun, cheaper and less critical, two sub-harmonic bunchers working at 650 MHz versus the main machine radio frequency (rf) that is at 1.3 GHz,

It is noteworthy that we are employing for the first time a second buncher, providing a greater flexibility in terms of beam energy and beam compression control.

INJECTOR DESIGN RATIONALE

The ERL injector/merger here proposed and sketched in Fig. 1 is based on consolidated technologies. A comparison with other main worldwide projects shows how with the scheme here presented is possible to inject at 4.5 MeV with a bunch charge of 100 pC, versus the 8 MeV and at 6.5 MeV, with a bunch charge of 77 pC, respectively of CBETA (Cornell) [3] and bERLinPro (HZB) [4]

Due to the high repetition rate, we opted for a DC-gun, considering as an example the 250 kV JAEA gun [5] whose design is solid. The beam extraction will be driven by an Ytterbium laser illuminating a Cs_2Te photo-cathode.

Figure 1 illustrates the beamline design downstream of the gun, starting with the solenoid for emittance compensation, followed by two normal-conducting (NC) rf bunchers operating at 650 MHz. The decision to use a sub-harmonic frequency of 650 MHz was based on considerations of beam dynamics. A longer rf bucket permits the trapping of longer cigar-shaped electron bunches, which typically exhibit lower emittance. Moreover, a more linear accelerating field offers significant benefits for energy spread reduction and longitudinal beam compression.

Downstream of the bunchers, the beam energy boost (at ~ 4.5 MeV) is done with three 1.3 GHz two-cells SC cavities ([6]).

Downstream the injector booster, there is a quadrupoles triplet to match the beam to the dogleg.

As previously emphasized, the injection of a high brightness low energy beam into an ERL results in significant SC forces. These forces lead to the remodulation of particle momenta within open dispersion regions, resulting in a loss

* marcello.rossetti@mi.infn.it

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPA019

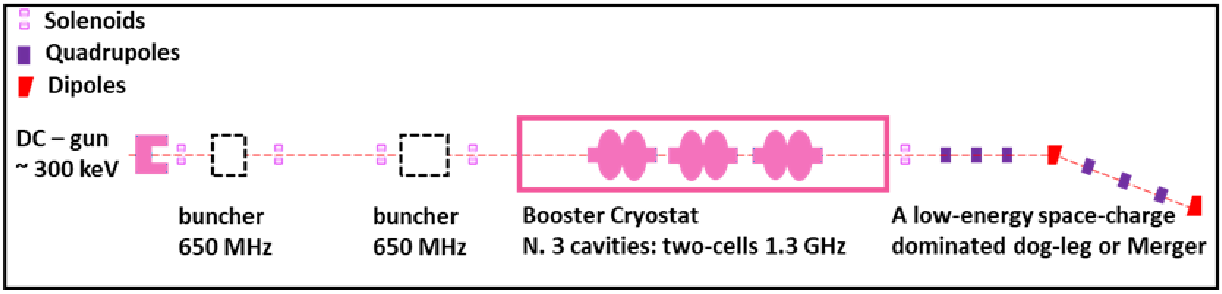

Figure 1: The ERL injector schema: the DC-gun, the two bunchers, the injector booster and the low energy dogleg.

of achromaticity during beam transport. This phenomenon is similar to the effects observed in magnetic compressors or arc compressors due to the presence of Coherent Synchrotron Radiation (CSR) emission [7].

The consequences of these effects include dispersion leakage that increases the beam emittance, the emergence of betatron kicks in dipoles, and a typical beam tilt in the $x - z$ and $p_x - z$ planes [8].

OPTIMIZATION METHODS

In this study, the entire injector beam line, including the downstream dispersive path, is affected by space charge forces. As a result, the simulations have been performed using the Astra code [9].

Beam line optimizations were carried out using GIOTTO [10] a genetic algorithm-based code that is well-suited for handling complex problems in which variables are strongly correlated in a non-linear manner [11].

In this study, GIOTTO was used to drive Astra in multi-objective optimizations.

OPTIMIZATIONS AND SIMULATIONS

The simulations presented in this section track a single bunch with a charge of 100 pC. The SC effects are computed along the whole path: a cylindrical mesh up to the dogleg, 3D Cartesian mesh inside of the dogleg.

The injector optimization has been done in two main steps: I) from the gun up to the dogleg, II) the dogleg/merger, as follows:

From the Gun up to the Dogleg

The BD solution up to the dogleg entrance resulting from the GIOTTO optimization is shown in Fig. 2. The spikes emittance in the figure corresponds to the solenoids entrance/exit fringing fields [12] and to the rf cavities

The most important points regarding this solution are explained step by step below and visible in Fig. 2:

Gun e-bunch generation by a Laser driven DC gun 250 kV/m [5]. Laser pulse shaping data is reported in Table 1.

Gun-solenoid A solenoid for the emittance compensation.

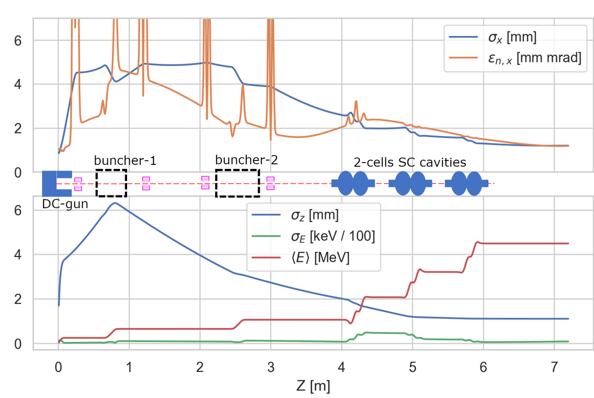

Figure 2: Upper plot: beam emittance and envelope. Lower plot: beam energy gain, bunch length and energy spread.

Table 1: Laser Pulse Shape Data at the Gun Photocathode

Parameter	Value
Flattop laser pulse	22.3 ps
Rise time	1.0 ps
σ_x transverse uniform	0.710 mm

Sb-buncher-I The first sub-harmonic buncher has a three-fold effect (see Fig. 2): I) envelope focusing, II) longitudinal phase space chirping and III) bunch acceleration to mitigate SC forces.

First drift Here thanks to the long. phase space chirping a ballistic bunching is performed.

Sb-buncher-II The second sub-harmonic buncher works in a similar way to the previous one.

Second drift Here the beam continues its bunching and its emittance oscillation reaches a relative minimum; this is the correct condition to inject the beam into the booster exploiting the velocity bunching [13] technique.

Injector booster, first cavity Here the bunch undergoes the VB being compressed and accelerated at the same time, meanwhile, it remains laminar and the emittance compensation is under control.

Injector booster, last two cavities With the beam entering into the last two 2-cells is possible to apply a quasi total beam energy spread compensation.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPA019

Drift before the dogleg Here the beam has 4.5 MeV of energy and shows optimal and stable beam parameters that are reported in Table 2.

The solenoids of the line (in Fig. 2 in pink) are 7 cm long capable to generate few hundreds of Gauss.

Table 2: Main Bunch Parameters at the Exit of the Booster

Parameter	Value
$\varepsilon_{n,x,y}$	1.2 mm-rad
$\sigma_{x,y}$	1.2 mm
σ_z	1.1 mm
E	4.5 MeV
σ_E	8.9 keV

The final BD lattice solution, up to the dogleg, resulting from the GIOTTO optimization is reported in the first part of Table 3. The optimization exploited also the laser pulse length and its spot size (Table 1) for a total of 13 parameters.

The Dogleg/Merger

Previous studies (e.g., [14, 15]), reporting space charge effects in ERL mergers, show how it is necessary to avoid strong beam focusing along the dispersive line to avoid an emittance degradation [2]. Ad hoc configurations [14, 15] can be used to overcome these effects, for example, the one named “zigzag" scheme [14, 15]. The merger line we use is a classic dogleg configuration: two dipoles (θ_{bend} = 20 deg and ρ = 0.28 m) and three quadrupoles (L = 0.1 m). Here we show how the SC effects can be well compensated by an appropriate beam line setting found using the GIOTTO code.

The final injector beam line knobs values resulting from the GIOTTO optimization are in Table 3.

Table 3: Final Injector Working Point after its Optimization

Solenoid		Peak Field [T]
$SOL-1$		0.0350
$SOL-2$		0.0220
$SOL-3$		0.0160
$SOL-4$		0.0283
$SOL-5$	(dogleg matching)	0.1263
RF cavitie	**E_{peak} [MV/m]**	**Φ_{inj} [deg] ***
Sb-buncher-I	3.4	-30.0
Sb-buncher-II	3.4	-70.0
I 2-cells cav.	11.5	-40.0
II 2-cells cav.	11.5	35.0
III 2-cells cav.	11.5	20.0
Quadrupole		**g [T/m]**
Q_1, Q_2, Q_3	(dogleg matching)	-0.060, -0.242, 0.551
Q_4, Q_5, Q_6	(η, η' comp.)	1.016, -0.717, 0.964

*Cavities Φ_{inj} refers to the crest of the rf wave that is at 0 [deg].

As it is visible in Fig. 3, the dispersion is perfectly closed on both planes ($\eta = 0$ and $\eta' = 0$). It is visible a small emittance increase of about ≈ 0.3 mm-mrad in x,y planes, due to a mild chromatic effect into quadrupoles. However, this increase is acceptable considering the very low injection energy.

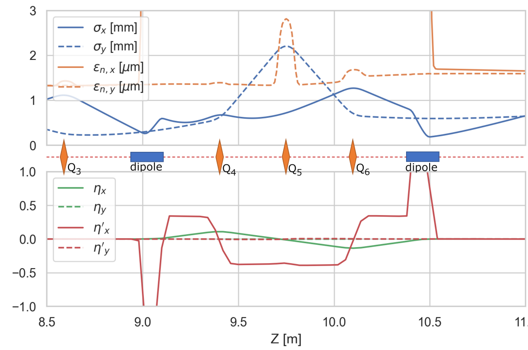

Figure 3: Dogleg beam tracking. The upper plot shows the beam envelopes and the beam emittance. The lower plot shows vertical and horizontal dispersions (η), and first derivatives (η').

Table 4: Main Bunch Parameters at the Dogleg Exit

Parameter	Value
$\varepsilon_{n,x,y}$	1.60, 1.65 mm-mrad
$\sigma_{x,y}$	0.65, 0.65 mm
σ_z	2.0 mm
E	4.5 MeV
σ_E	26.0 keV

The doubled bunch length from 1.0 mm to 2.0 mm visible comparing Table 4 with Table 2 is not of concern; downstream of the ERL the beam can be further compressed taking advantage of a higher beam energy. The energy spread increases from 8.9 keV to 26.0 keV which is still a very low value. It is worth to note in Fig. 3 how GIOTTO restores a quasi cylindrical beam on the transverse plane at the end of the dispersive path.

CONCLUSION

This paper presents a high performing low energy ERL injector showing innovative solutions. A layout based on sub-harmonic bunchers performing very well in emittance preservation, bunch compression and energy spread suppression. These benefits in the BD allow us to use a non-cutting edge gun, which is a clear plus in terms of costs and feasibility. Our solution is addressed thanks to well established BD concepts, e.g., cigar-like distributions and the VB technique [16]. It is new also the use of two bunchers instead of one, both with an ad hoc λ_{cell} for a better control of the beam phase slippage (versus the accelerating wave) and the VB itself. Further these established BD concepts, we exploit the breakthrough force of the GIOTTO [10] code to cope with the complex problem of a space-charge dominated dispersive path, avoiding the use of peculiar dispersive path shapes [14, 15].

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPA019

REFERENCES

[1] M. Abo-Bakr and M. Arnold, "Working Group Summary: ERL Facilities," in *63rd ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs*, 2019, FRCOYBS01. doi:10.18429/JACoW-ERL2019-FRCOYBS01

[2] L. Serafini and J. B. Rosenzweig, "Envelope analysis of intense relativistic quasilaminar beams in rf photoinjectors:ma theory of emittance compensation," *Phys. Rev. E*, vol. 55, pp. 7565–7590, 6 1997. doi:10.1103/PhysRevE.55.7565

[3] C. Gulliford *et al.*, "Demonstration of low emittance in the cornell energy recovery linac injector prototype," *Phys. Rev. Spec. Top. Accel Beams*, vol. 16, p. 073 401, 7 2013. doi:10.1103/PhysRevSTAB.16.073401

[4] M. Abo-Bakr *et al.*, "Status report of the berlin energy recovery linac project berlinpro," in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, 2018, pp. 4127–4130. doi:10.18429/JACoW-IPAC2018-THPMF034

[5] R. Nagai, R. Hajima, and N. Nishimori, "Magnetic emittance suppression using a bucking coil for a dc photocathode electron gun," *Rev. Sci. Instrum.*, vol. 83, no. 12, p. 123 303, 2012. doi:10.1063/1.4772397

[6] A. Burrill *et al.*, "First Test Results of the BERLinPro 2-cell Booster Cavities," in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15), Richmond, VA, USA, May 3-8, 2015*, Richmond, VA, USA, 2015, pp. 2765–2767. doi:10.18429/JACoW-IPAC2015-WEPMA010

[7] M. Rossetti Conti, A. Bacci, A. R. Rossi, V. Perillo, and L. Serafini, "Optimization of the arc compressor performance in the MariX free electron laser," *Journal of Physics: Conference Series*, vol. 1596, no. 1, p. 012 035, 2020. doi:10.1088/1742-6596/1596/1/012035

[8] M. W. Guetg, B. Beutner, E. Prat, and S. Reiche, "Optimization of free electron laser performance by dispersion-based beam-tilt correction," *Phys. Rev. Spec. Top. Accel Beams*, vol. 18, p. 030 701, 3 2015. doi:10.1103/PhysRevSTAB.18.030701

[9] K. Floettmann, *Astra: A space charge tracking algorithm*, 1997. http://www.desy.de/~mpyflo/

[10] A. Bacci, V. Petrillo, and M. Rossetti Conti, "Giotto: A genetic code for demanding beam-dynamics optimizations," in *Proc. 7th Int. Particle Accelerator Conf. (IPAC 2016): Busan, Korea, May 8-13, 2016*, 2016, pp. 3073–3076. doi:10.18429/JACoW-IPAC2016-WEPOY039

[11] D. S. Weile and E. Michielssen, "Genetic algorithm optimization applied to electromagnetics: A review," *IEEE Trans. Antennas Propag.*, vol. 45, no. 3, pp. 343–353, 1997. doi:10.1109/8.558650

[12] V. Kumar, "Understanding the focusing of charged particle beams in a solenoid magnetic field," *Am. J. Phys.*, vol. 77, no. 8, p. 737, 2009. doi:10.1119/1.3129242

[13] L. Serafini and M. Ferrario, "Velocity bunching in photoinjectors," *AIP Conference Proceedings*, vol. 581, no. 1, pp. 87–106, 2001. doi:10.1063/1.1401564

[14] V. N. Litvinenko, R. Hajima, and D. Kayran, "Merger designs for erls," *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 557, no. 1, pp. 165–175, 2006, Energy Recovering Linacs 2005. doi:10.1016/j.nima.2005.10.065

[15] D. Kayran, I. Ben-Zvi, R. Calaga, X. Chang, J. Kewisch, and V. N. Litvinenko, "Optics for high brightness and high current erl project at bnl," in *Proc. 21th IEEE Particle Accelerator Conf. (PAC2005)*, IEEE, 2005, pp. 1775–1777. doi:10.1109/PAC.2005.1590909

[16] M. Ferrario *et al.*, "Experimental demonstration of emittance compensation with velocity bunching," *Phys. Rev. Lett.*, vol. 104, no. 5, p. 054 801, 2010. doi:10.1103/PhysRevLett.104.054801