

AN OPTIMIZATION OF A DC INJECTOR WITH MERGER FOR THE ENERGY RECOVERY LINAC UPGRADE TO THE APS*

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Abstract

An energy recovery linac (ERL) is a potential candidate for an Advanced Photon Source (APS) upgrade at Argonne National Laboratory. A high-DC-voltage photocathode-gun-based electron injector [1] was previously investigated to meet the ultra-low emittance requirement. Recently, the modeling was extended to include a merger using the fully three-dimensional tracking simulation code IMPACT-T [2]. A multiobjective numerical optimization was performed with the goal of delivering a 10-MeV, 19-pC bunch with a normalized transverse emittance less than $0.1 \mu\text{m}$ at the entrance of the linac. In this paper we show the optimum performance obtained.

INTRODUCTION

The APS is a storage-ring-based x-ray source. After years of continuous improvement and state-of-the-art performance, major accelerator upgrades are being investigated. In principle, an ERL-based x-ray source should deliver high-flux x-ray beams with much higher beam brightness and far shorter pulse durations than those available from storage rings.

The injector is a key element of the ERL@APS upgrade since, unlike a ring, the beam properties are largely determined by the injector system. We must deliver a high-average-current beam with very small transverse and longitudinal emittances, at a sufficiently high energy that space charge effects are under control.

The APS ERL project has two proposed working modes, namely, high flux (HF) and high coherence (HC) modes [3]. We present here the detailed optimization of injector configuration for both modes, parameters of which are given below.

MODELING AND PARAMETERS

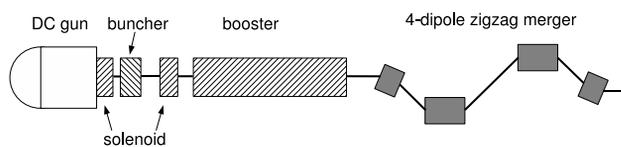


Figure 1: Schematic layout of DC injector with merger.

The high-DC-voltage photocathode-gun-based electron injector for ERL@APS has the “standard” features of both the Jefferson Lab and Cornell concepts, being composed of a high-DC-voltage photocathode gun coupled with an rf buncher and a TESTLA-type 9-cell rf cavity operating at 1.3 GHz. The first solenoid immediately following the DC gun is responsible for transverse space-charge emittance compensation. The second solenoid located after the buncher matches the beam optics to the booster and also compensates emittance growth from space charge.

The DC injector was initially modeled using ASTRA [4]. However, the lack of support for bending magnets prevented us from integrating a merger into the simulation. IMPACT-T was adopted because it is able to model a wide range of beamline elements and calculate fully 3-dimensional space charge as well as the coherent synchrotron radiation (CSR) wake. A side-by-side comparison with the simulation results from ASTRA demonstrated that IMPACT-T is suitable for these simulations. Merger modeling was further crosschecked using GPT [5], showing good agreement on the emittance evolution in the bending plane.

A merging system between the injector and linac combines the low-energy beam from the DC injector and the high-energy beam while, ideally, preserving the transverse emittance of the low-energy beam. The zigzag-type merger [6] is compatible with the emittance compensation scheme as well as providing an achromatic condition for space-charge-dominated beam. As shown in Fig. 1, a 4-dipole zigzag is currently used in our design.

The 4-dipole zigzag has an achromatic lattice [6]: 10° bend, 40-cm drift, -20° bend, 81.6-cm drift, 20° bend, 40-cm drift, 10° bend. All bending magnets have a flat field with a bending radius of 86 cm. IMPACT-T models bending magnets as a constant vertical field region and two fringe field regions on both ends of the constant-field part. The fringe field’s falloff is modeled by an eight-parameter

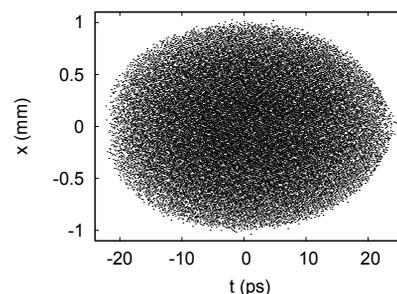


Figure 2: The ellipsoidal drive-laser.

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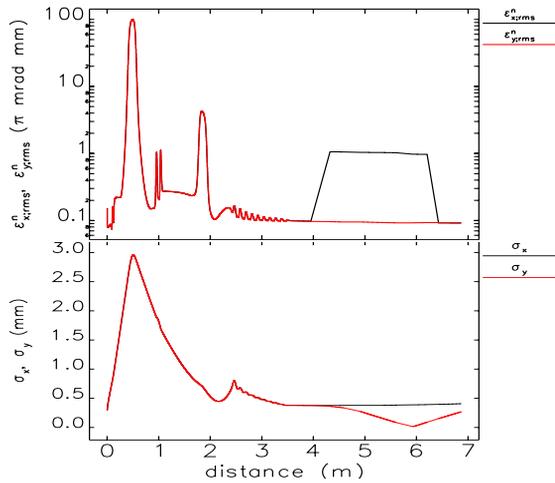


Figure 3: Transverse normalized rms emittance and rms beam size for 19 pC/bunch.

Enge function. The Enge coefficients used in our simulation are from measurements at SLAC [7].

The shaping of the photocathode drive laser pulse is critical for achieving submicron beam emittances. The ellipsoidal laser pulse has been demonstrated to have the potential to deliver lower final transverse emittance than a uniform cylindrical or pancake drive laser distributions [8]. As in [1], an experimentally feasible quasi-ellipsoidal bunch with uniform charge density is used in simulation. As shown in Fig. 2, the recess in the leading edge and the protrusion at the trailing edge distort the ideal ellipsoidal shape. The transverse size of the distribution is 0.93 mm in FWHM and can be safely scaled to a target rms size. However, the duration of the laser pulse, 10 ps rms, can not be easily scaled because of the fixed size of the distortions.

OPTIMIZATION AND RESULTS

The large number of variables and the complexity of the physics in the injector makes analytical optimization impossible. Hence, we used the multi-objective optimization technique [9] that was used successfully for the Cornell design. A parallel geneticOptimizer [10] based on the nondominated sorting genetic algorithm II [11] has been developed at APS. The optimizer has the flexibility of working with essentially any program or group of programs as well as an unlimited number of objectives and constraints.

There are ten optimization variables whose value will be decided by the optimizer for each specific trial solution: laser spot size; DC gun voltage; 1st solenoid strength; 2nd solenoid strength and position; buncher cavity gradient and phase; and booster cavity gradient, phase and position. After a simulation, a few constraints are calculated so that the optimizer can eliminate trial solutions with beam loss, overlapping elements, or violation of requirements. The transverse emittances and DC gun voltage, appropriately normalized, are used as penalty values, leading the opti-

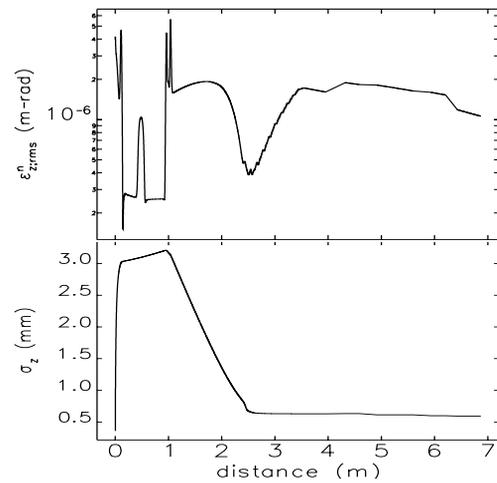


Figure 4: Longitudinal normalized rms emittance and rms bunch length for 19 pC/bunch.

mization toward solutions with as low as possible transverse emittances and DC gun voltage.

The geneticOptimizer performs non-dominated sorting of the penalty values and extracts parameters of rank 1 trial solutions into a “best solutions” file. These best solutions are then used to breed the next generation of trial solutions. Beam parameters of a typical rank 1 solution after 19,000 iterations are tabulated in Table 1, along with the requirements to the ERL@APS HC mode for comparison. The corresponding machine configuration is tabulated in Table 2. The evolution of normalized emittances and bunch sizes are depicted in Figs. 3 and 4. Beam phase space at the end of simulation is shown in Fig. 5.

The effective thermal energy E_{th} of the photocathode is assumed to be 24.5 meV in the optimization. The thermal emittance of the photocathode is $\epsilon_{n,rms} = \sigma \sqrt{(E_{th}/m_0c^2)}$ [9], where σ is the rms laser spot size and m_0c^2 is the rest mass of the electron. In the optimum solu-

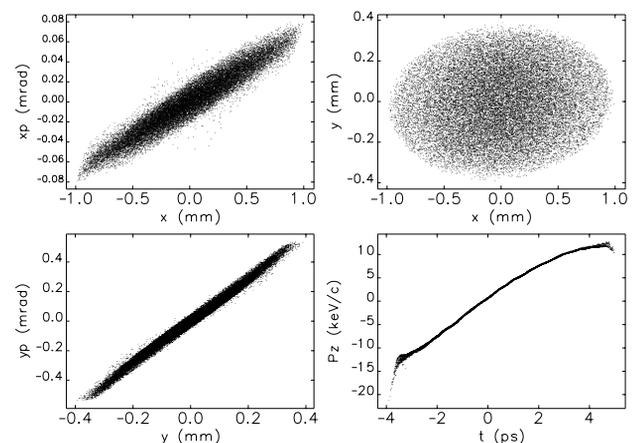


Figure 5: The phase space at the end of simulation for 19 pC/bunch: upper left (x, x'); upper right (x, y); bottom left (y, y'); bottom right (t, P).

Table 1: 19 pC/bunch Results and HC Mode Requirements

	Simulation	Requirement
Energy (MeV)	12.39	10
Energy spread (keV)	6.93	140
rms bunch length (mm)	0.59	0.6
Normalized $\varepsilon_x/\varepsilon_y$ (μm)	0.09/0.09	0.1/0.1
Normalized ε_z (μm)	1.06	1.6

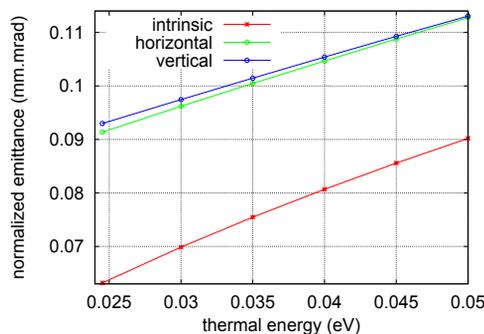


Figure 6: The normalized emittances as a function of the thermal energy on photocathode, for HC mode.

tion above, the assumed normalized intrinsic emittance was $0.063 \mu\text{m}$. Keeping all parameters for machine configuration unchanged, the simulations were performed at various thermal energies up to 50 meV to simulate variation in the thermal emittance due to the choice of drive laser and photocathode material. The results are shown in Fig. 6.

Next, an optimization for HF mode was performed starting from the optimal result for HC mode. Solutions satisfying all requirements emerged after a mere 4,000 iterations. Beam parameters of a typical rank 1 solution are tabulated in Table 3, along with the HF mode requirements. The corresponding machine configurations for both modes are tabulated in Table 2. Even though low DC gun voltage is sought by the optimization, the very high DC gun voltage of ~ 750 MV appears to be required for ultra-low final transverse emittances.

Table 2: Decision Variable Values Leading to Beam Parameters Shown in Tables 1 and 3

	HC	HF
Laser spot size XYrms (mm)	0.288	0.469
DC gun voltage (kV)	720.95	752.45
1st solenoid strength (T)	0.039	0.040
2nd solenoid strength (T)	0.029	0.027
Buncher cavity gradient (MV/m)	2.696	3.222
Buncher cavity phase (degree)	113.8	103.0
Booster cavity gradient (MV/m)	22.023	22.296
Booster cavity phase (degree)	324.2	312.4

Table 3: 77 pC/bunch Results and HF Mode Requirements

	Simulation	Requirement
Energy (MeV)	12.28	10
Energy spread (keV)	30.70	140
rms bunch length (mm)	0.514	0.6
Normalized $\varepsilon_x/\varepsilon_y$ (μm)	0.27/0.27	0.3/0.3
Normalized ε_z (μm)	0.97	1.6

CONCLUSION

We have modeled a DC injector design for ERL@APS with a zigzag merger using the beam dynamics program IMPACT-T. Numerical optimization gives machine configurations for which the requirements of ERL@APS HC mode and HF mode are met. However, the ultra-low emittance is highly dependent on the very high DC-gun voltage of ~ 720 kV for HC mode and ~ 750 kV for HF mode, while the experimentally achievable gun voltage is ~ 350 kV. The zigzag merger is seen to be well suited to preserving a very low emittance electron beam. In our 3-D simulation using IMPACT-T, essentially no emittance growth is seen from the merger for even 77 pC/bunch.

Having obtained these optimized configurations, our next step will be to integrate them into a start-to-end model of a full ERL. This will permit more reliable evaluation of the performance of the ERL, including collective effects (e.g., CSR) and jitter.

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