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

Yin-e Sun[1,2], Hairong Shang[1], Michael Borland[1], Yuelin Li[1], Katherine Harkay[1]
[1]Advanced Photon Source, Argonne National Lab., Argonne, IL 60439, USA
[2]Accelerator Physics Center, Fermilab, Batavia, IL 60510, USA

Abstract

An energy recovery linac based light source is a potential revolutionary upgrade to the Advanced Photon Source (APS) at Argonne National Laboratory. The concept relies on several key research areas, one of which is the generation of ultra-low emittance, high-average-current electron beams. In this paper, we present our investigation of a dc-gun-based system for ultra-low emittance bunches in the 20 pC range. A parallel multi-objective numerical optimization is performed in multi-parameter space. Parameters varied include experimentally feasible drive-laser shapes, the DC gun voltage, the thermal energy of the emitted photo-electrons and other electric or magnetic field strengths, RF cavity phase etc. Our goal is to deliver a $\sim$10 MeV, 20 pC bunch at the entrance of the linac with an emittance of 0.1 μm or lower, rms bunch length of 2 $\sim$ 3 ps, and energy spread no larger than 140 keV. We present the machine parameters needed to generate such an injector beam, albeit without a merger.

INTRODUCTION

The APS is a storage-ring based light source. Fundamental physics principles governing a storage ring determine the electron beam emittance as well as its fractional energy spread. It is difficult to improve the beam quality dramatically solely by upgrading the storage ring[1], due to the requirement to keep the energy fixed at 7 GeV while accomodating the existing circumference and number of sectors. In contrast, the emittance of the electron beam in a linac is inversely proportionally to the beam energy, as the normalized emittance is constant. Therefore emittance much smaller than the APS storage ring is possible in a linac of the same beam energy. However, high average current (e.g., 100 mA) is needed for a facility to operate as a state-of-art light source. With 7 GeV beam energy, this corresponds to 700 MW beam power. The only feasible way to operate such a linac-based light source is to have the beam energy recovered [2] after it is used to generate light.

One of the most challenging aspects of the ERL design is the injector, as it requires unprecedented average current with extremely small normalized emittance. Currently there are several DC guns in operation for the ERLs, most notably at TJNAF [3]. However, none of these operating guns meets the requirements of the ERL upgrade at APS [4]. Some high performance dc-gun-based system have been investigated for ultra-low emittance beams [5, 6]. None of these analysis delivers the desired charge (20 pC or higher) while including the critical merger between the injector and the linac. In this paper, we present a first step in our efforts, namely, the design of a dc-gun-based injector without a merger system.

OPTIMIZATION METHOD

This injector design is developed using the multi-objective optimization techniques, similar to those employed by Bazarov et al. [5]. At APS, a global parallel optimizer named GeneticOptimizer already existed[7]. Originally it accepted a single penalty function. For the present work, non-dominated sorting was incorporated to perform multi-objective optimization. The current version of GeneticOptimizer is able to do both single object and multi-objective optimization. For single objective optimization, the parents chosen by GeneticOptimizer are those who have the smallest penalty value, while for multi-object optimization, the parents are those with rank 1 after non-dominated sorting. The beam dynamics simulation program used is ASTRA [8], which includes space charge forces.

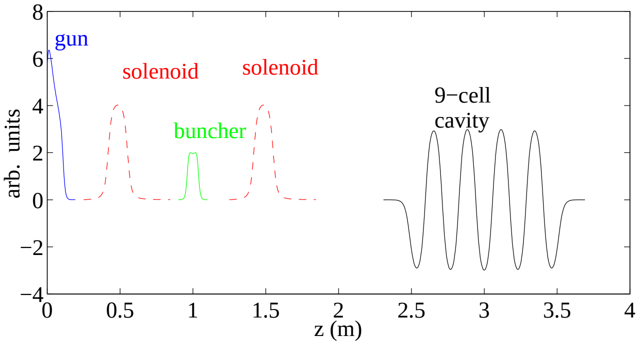

Figure 1: The field maps of the injector elements along the beamline.

INJECTOR AND DRIVE-LASER

The photoinjector we considered is similar to the TJNAF FEL injector [9]. A DC photo emission electron source

---

* Work supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.

(the DC gun) produces electron bunches. The bunches are compressed via ballistic bunching using a 1.3 GHz buncher cavity [10], and then further accelerated to ∼10 MeV in a TESLA type cavity [11]. The low energy section also incorporates two solenoidal lenses for the control of the beam's transverse envelope and emittance compensation [12]; see Fig. 1 for the relative positions of these elements in the beamline.

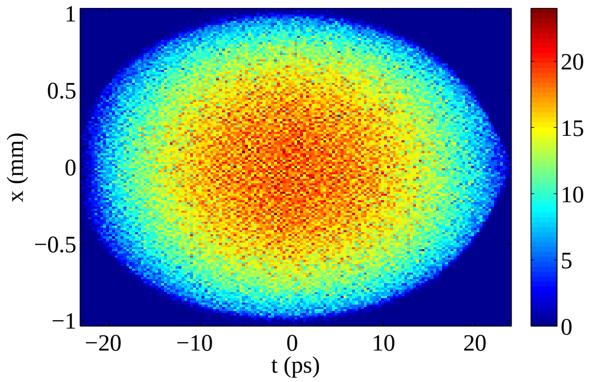

Figure 2: The (*x*,*t*) projection of the ellipsoidal drive-laser.

To achieve sub-micron beam emittances, the shaping of the photocathode drive laser pulse is critical. In our simulations, several drive laser distributions are explored: beer-can, pancake, and "egg" (which is a non-ideal ellipsoid). The beer-can has a transversely uniform, longitudinally flat distribution; the pancake is an ultra-short (∼10s of fs rms) pulse; for the egg distribution, a 3-D ellipsoidal surface is filled with unform beam density. Both the beer-can [13] and pancake [14] shaped laser pulse have been experimentally demonstrated, while the ellipsoidal laser pulse is under developement [15, 16]. In Fig. 2, an example of the laser egg intensity profile is shown in the (*x*,*t*) plane; some structures exist in the two ends of the ellipse.

OPTIMIZATION RESULTS

The optimization variables include the following: drive-laser transverse spot size and longitudinal pulse length, buncher cavity voltage and phase, booster cavity voltage, phase and position, solenoid strengths and positions.

In Fig. 3, we plot simulation results using the three types of photocathode drive laser pulses. We see the ellipsoidal laser pulse gives slightly smaller normalized transverse emittance than the beer-can. For the pancake case, the longitudinal phase space is much smaller but the transverse emittance is doubled; see Table. 1. In Luiten's scheme [17], to produce an ellipsoidal electron beam from a pancake laser, the following conditions are required

$$\frac{eE_0\tau_l}{mc^2} \ll \frac{\sigma_0}{\varepsilon_0 E_0} \ll 1, \qquad (1)$$

where ε_0 is the permittivity of free space. In our pancake simulation, the total emission time τ_l is about 80 fs, the accelerating gradient on cathode is about E_0=8.2 MV/m, therefore we have $\frac{eE_0\tau_l}{mc^2} = 3.9\times10^{-4} \ll \frac{\sigma_0}{\varepsilon_0 E_0} \simeq 0.5$. The right hand inequality of Eq. (1) is marginally satisfied. This explains the larger emittance from the pancake simulations, which is due to the fact that the accelerating gradient on the cathode is relatively low compared with a rf gun, and the transverse laser spot size cannot be arbitrarily increased as it is proportional to the thermal emittance [18]. In the simulation presented in Fig. 3, the thermal energy of the electron beam is assumed to be 40 meV at the cathode for all kinds of laser shapes.

Table 1: Optimized parameters for various drive laser

	beer-can	egg	pancake
DC gun voltage (kV)	740	748	728
laser length σ_t(ps)	9.7	10.4	13.2×10^{-3}
laser spot σ_0 (mm)	0.32	0.30	0.43
thermal emit. ε_{th}(μ m)	0.08	0.07	0.10
norm. emit. ε_x^n(μ m)	0.15	0.13	0.30
bunch length σ_z (mm)	0.64	0.80	0.49
uncor. energy spread (keV)	4.69	4.93	0.83

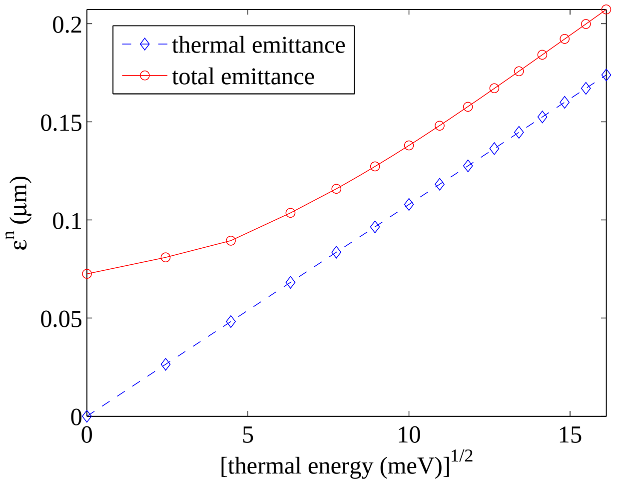

Figure 4: The normalized total beam emittance and the thermal emittance as a function of the thermal energy on the cathode; DC gun voltage is 735 keV.

As the thermal emittance depends on the choice of drive-laser and photocathode material, we have performed further injector optimizations for different initial thermal energies. Without repeating the optimized input variable results, we varied the input beam thermal energy and tracked the particles through the injector. The results are shown in Fig. 4.

The upper limit of the dc gun voltage in the optimization shown in Fig. 3 is 750 kV. However it should be noted that in dc guns under development, voltages have so far been

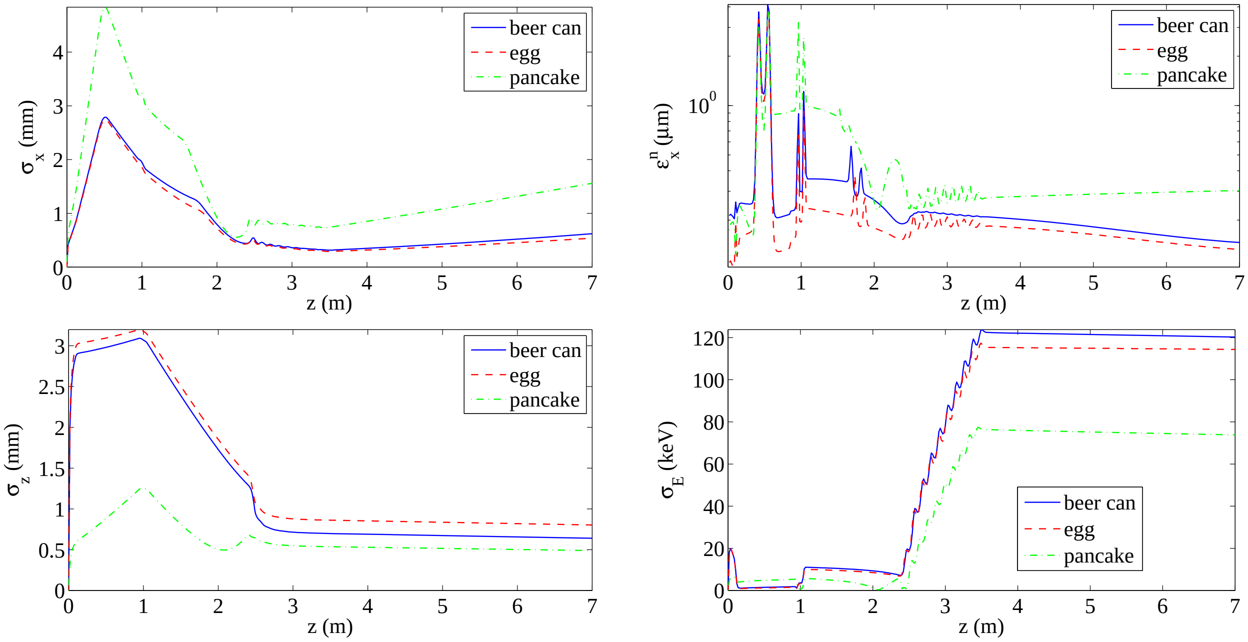

Figure 3: Beam parameter evolution along the injector beam line: the transverse beam size σ_x, normalized transverse emittance ε_x^n, rms bunch length σ_z and the energy spread σ_E.

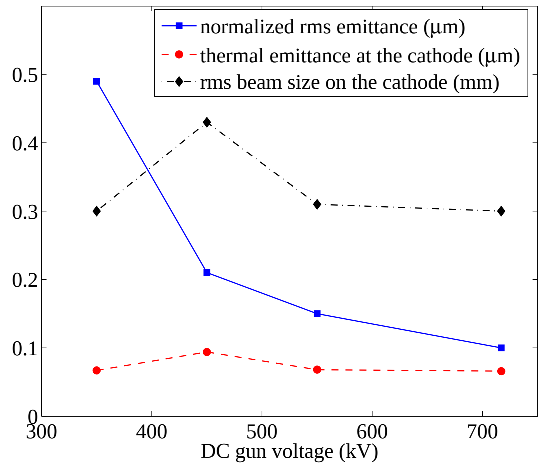

Figure 5: The normalized transverse emittance at various DC gun voltages.

limited to ∼350 kV due to technical issues. Several groups are working to improve this technology, including Cornell, TJNAF, and Daresbury. Nevertheless, we optimized the injector at several fixed DC gun voltage values using the ellipsoidal laser, as shown in Fig. 5. A significant drop in the beam emittance occurs between 350 and 450 keV gun voltage; further increase of the gun voltage leads to improved emittance at a slower rate.

The authors thank Philippe Piot for helpful discussions.

REFERENCES

[1] A. Xiao *et al.*, in Proc. PAC 2007, pp. 3447-3449 (2007).

[2] M. Tigner, Nuovo Cimento **37**, pp 1228-1231 (1965).

[3] G. Neil *et al.*, Phys. Rev. Lett. **84**,662 (2000).

[4] M. Borland *et al.*, Nucl. Instrum. Methods A **582** (2007) 54-56 .

[5] I. Bazarov, and C. Sinclair, Phys. Rev. ST Accel. Beams **8**, 034202 (2005).

[6] R. Hajima, and R. Nagai, Nucl. Instrum. Methods A **557** (2006) 103-105.

[7] M. Borland, H. Shang, unpublished program.

[8] K. Flöttmann, http://www.desy.de/ mpyflo/

[9] P. Piot, in Proc. of EPAC 1998, pp. 1447 - 1449 (1998).

[10] I. Bazarov, *USPAS 2005: Recirculated and Energy Recovered Linacs*.

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

[12] C. K. Sinclair, Nucl. Instrum. Methods A **318** (1992) 410-414 .

[13] C. Vicario *et al.*, in Proc. of PAC 2007, pp. 1004-1006 (2007) .

[14] P. Musumeci *et al.*, Phys. Rev. Lett. **100**, 244801 (2008).

[15] Y. Li, and J. W. Lewellen, Phys. Rev. Lett. **100**, 074801 (2008).

[16] Y. Li, and S. Chemerisov, Opt. Lett. **33**, 1996 (2008).

[17] O. J. Luiten *et al.*, Phys. Rev. Lett. **93** ,094802 (2004).

[18] J. D. Lawson, "the physics of charged-particle physics",Clarendon Press, Oxfod, 1988.