

# SIMULATION STUDY OF A NORMAL-CONDUCTING RF PHOTOINJECTOR FOR ERL X-RAY SOURCES \*

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## Abstract

We investigate the potential of low-frequency normal-conducting rf guns for driving multi-GeV ERL-based x-ray sources. Using genetic optimization, we found solutions for a 325-MHz gun that can generate electron bunches competitive to the envisioned DC injectors. Such an injector may offer an alternative solution for driving 1.3-GHz ERL-based light sources. Furthermore, it enables a new multi-beam scheme for either reducing ERL duty factor to save cost or for enhancing light-source performance by a factor up to four.

## MOTIVATION

Envisioned ERL-based x-ray light sources promise much higher performance than 3<sup>rd</sup>-generation light sources [1, 2]. Such promises rely on high-brightness high-average-current electron beams from photoinjectors. Currently, the required photoinjector performance is still beyond the state of the art, but appears to be reachable. In order to have beam current comparable to storage-ring light sources, average current on the order of 100 mA is desired from photoinjectors. This leads to cw injectors with relatively low bunch charge to simultaneously achieve low emittance and high average current. There are three basic types of photoinjectors for such applications: DC gun, superconducting rf gun, and low-frequency normal-conducting rf (NCRF) gun. The DC gun with GaAs cathode is the leading contender and is being pursued at Cornell University. The major difficulty is to provide over 700-kV DC voltage without breakdown in order to yield about 7 MV/m accelerating field on the cathode, which is critical for combatting space-charge forces to produce the required low emittance. The superconducting gun can potentially provide a much higher rf accelerating field on the cathode without unmanageable rf heat load on the cavity. The major difficulties are complex superconducting rf infrastructure, integration of removable cathode, and implementation of focusing field for emittance compensation. Normal-conducting rf guns are the workhorses for state-of-the-art FELs, but are usually limited by rf heat load for cw operations. Nonetheless, the 433-MHz Boeing gun reached 32-mA current at 25% duty factor over a decade ago [3]. Recent efforts on high-current cw NCRF guns are the LANL/AES 700-MHz gun [4] and the LBNL VHF gun [5]. See [6] for a recent survey of more injector options.

Our interest here is in low-frequency NCRF photoinjectors. Such a gun has many attractive features: a) it can provide cathode field much higher than 7 MV/m, which DC guns are struggling to produce; b) it can use long bunches near cathodes similar to that of DC guns to reduce transverse space-charge forces, thanks to long rf wavelength; c) it can use solenoid focusing adjacent to the cavity for emittance compensation, thanks to the normal-conducting cavity; d) the gun cavity can be compact longitudinally even at fairly low frequency, thus reducing the distance low-energy electrons have to travel and leaving space for transverse focusing close to the cathode; e) it can provide sufficiently good vacuum for using a semiconductor cathode such as GaAs (as foreseen in both the LANL/AES 700-MHz gun and the LBNL VHF gun); f) it avoids complex superconducting gun technology or special expertise for high-voltage DC guns, while NCRF technology is commonplace in accelerator labs. Most of these features are advantageous for producing low-emittance beams. However, a low-frequency injector requires much higher bunch charges in order to obtain the same average current (Table 1), which counteracts the above advantages. Furthermore, significant bunch-length reduction in the injectors is often needed, which may degrade transverse brightness. Thus our first goal is to investigate whether a low-frequency NCRF gun can produce beams comparable to the envisioned DC injectors. In addition, such high-charge, low-frequency guns are fundamental to a new ERL light-source scheme that relies on merging multiple subharmonic beams into an ERL in order to either lower ERL duty factor for cost savings or enhance light-source performance [7]. Using genetic optimization of an injector layout similar to a DC injector, we found solutions for a 325-MHz gun that can generate electron bunches competitive with DC injectors for the envisioned ERL x-ray sources [2]. Merging beams from such injectors can potentially reduce ERL duty factor by as much as a factor of 4 or increase light source performance by a similar factor with cw ERLs.

Table 1: Bunch charges needed for a 100-mA average current beam under various injector/linac rf frequencies and duty factors. 77 pC is for the envisioned high-flux mode 1.3-GHz ERL x-ray sources with normalized beam emittance  $\epsilon \leq 0.3 \mu\text{m}$ . This study aims at a 325-MHz gun with the same beam quality at 0.3 nC for applications along the diagonal (multi-beam injection is required for  $D < 1$ ).

	325 MHz	650 MHz	1300 MHz
D=1	0.3 nC	0.15 nC	77 pC
D=1/2	0.6 nC	0.3 nC	0.15 nC
D=1/4	1.2 nC	0.6 nC	0.3 nC

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## INJECTOR LAYOUT

Except for much higher cathode field and bunch charge, low-frequency rf guns are expected to be similar to DC guns in terms of beam dynamics. Thus, for simplicity and easy comparison, we adopted the Cornell DC gun layout but replaced the DC field with a 325-MHz rf cavity. We chose this frequency because it is the 4<sup>th</sup> subharmonic of the 1.3-GHz linac frequency. The normal-conducting gun cavity is adopted from an LBNL preliminary design as shown in Fig. 1. Both rf breakdown and heat load can limit the field strength. The Kilpatrick's empirical breakdown limit  $E_K$  [MV/m] at rf frequency  $f_{rf}$  [MHz] is given by  $f_{rf} = 1.64E_K^2 e^{-8.5/E_K}$ , which yields  $E_K \simeq 18$  MV/m at 325 MHz. Present-day rf technology can often reach over  $1.5E_K$  before breakdown. Thus we used a 25-MV/m cathode field for this study. Thermal analysis in the LBNL design study suggests manageable rf heat load at such a field level. For simplicity, we used 650-MHz TESLA-style cavities for all the other cavities: a single-cell cavity operating at zero-crossing for bunching and four two-cell cavities for extra bunching and acceleration. We limit these cavity field strengths to about 20 MV/m, which is realistic for superconducting cavities. For the focusing solenoids, we simply used the field profile from the Cornell DC gun design. The magnitude of the on-axis electric field and magnetic field are shown in Fig. 2. The buncher cavity may be normal-conducting with a different shape. Most of the accel-

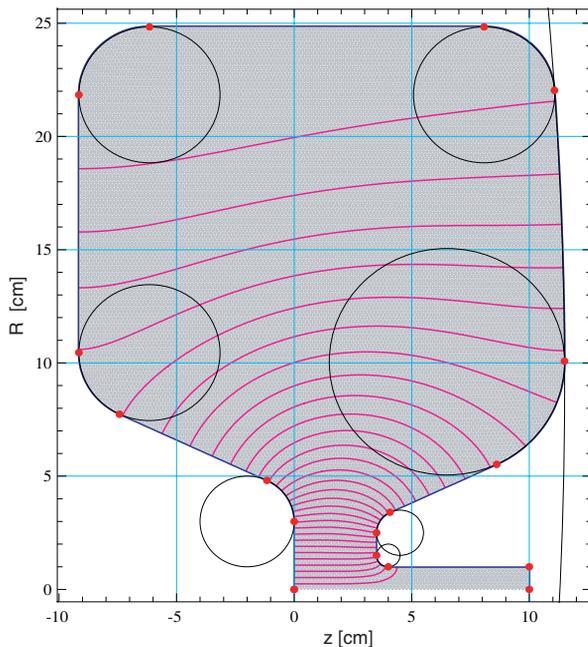


Figure 1: Geometry and field pattern of a 325-MHz gun cavity, adopted from an LBNL design by courtesy of J. Staple. The meshed area is the cross section of cavity interior, outlined by lines and arcs joined at the red dots. The purple lines are the field pattern generated with LANL Superfish software. The cathode is located at the origin.

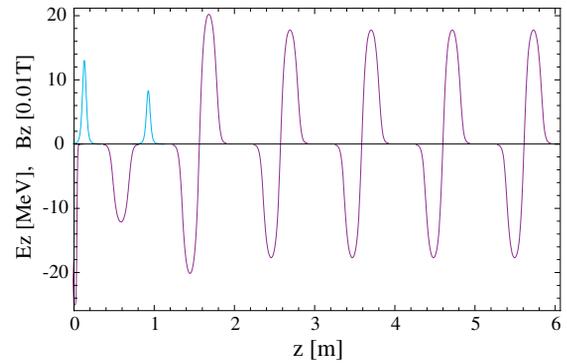


Figure 2: Amplitudes of on-axis electric (purple) and magnetic (cyan) fields from cavities and solenoids.

ating cavities may be able to use 1.3-GHz cavities since the bunch length is already sufficiently short. Using two-cell cavities limits the power that rf input couplers have to handle (there is no energy recovery in the injectors). The spaces between the cavities are intended for rf ports such as input couplers and HOM dampers. Note that this is a preliminary design to investigate potential beam quality.

## SIMULATION/OPTIMIZATION RESULTS

The program ASTRA [8] is used for injector simulation with parameters (e.g., the grid for space-charge computation) similar to the Cornell DC gun simulation [9] for easy comparison. Laser pulse length, cavity and solenoid locations, and their field strengths and rf phases are optimized with a multiobjective genetic optimizer, which is an SDDS-toolkit implementation of the NSGA-II algorithm [9, 10]. To avoid complications associated with 3D laser pulse shaping, we used beer-can pulses at the cathode for this study, showing that it is sufficient for the baseline performance. For the cathode, we assumed GaAs for its low thermal emittance based on the Cornell study. In fact, we used the initial beer-can distribution files from the Cornell DC gun simulations and simply scaled the bunch charge, size, and length in ASTRA.

After extensive searches of optimal solutions using a multiobjective genetic optimizer on our local computer clusters, sufficiently good solutions were found; Table 2

Table 2: Basic Beam Parameters of Two Potential Solutions

bunch charge $Q$ [nC]	0.077	0.3
laser spot size $\sigma_x$ [mm]	0.26	0.6
laser pulse length $\sigma_t$ [ps]	6.1	9.0
emittance at cathode $\epsilon_n^0$ [ $\mu\text{m}$ ]	0.07	0.17
emittance at exit $\epsilon_n$ [ $\mu\text{m}$ ]	0.10	0.25
bunch length at exit $\sigma_z$ [mm]	0.42	0.61
energy spread at exit $\sigma_E$ [keV]	20.6	33.2
beam energy at exit $E$ [MeV]	22.9	23.1

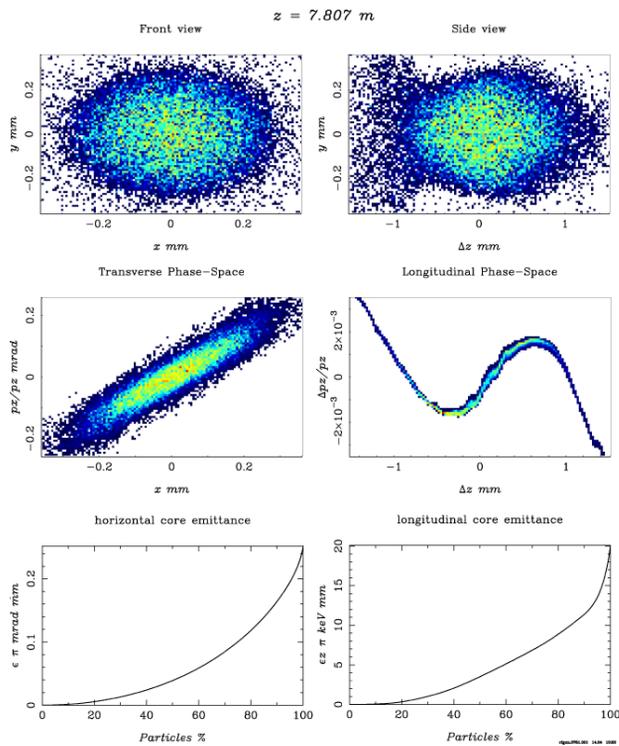


Figure 3: Bunch images in configuration and phase spaces show a well-formed bunch of 0.3 nC, despite halos from the tails.

lists the potential beam parameters. In our optimization, we aimed at 0.3 (0.1)  $\mu\text{m}$  transverse emittance for the high charge (coherence) mode with bunch charge of 0.3 (0.077) nC and rms bunch length of 0.6 mm without correlated energy spread. No constraints on beam energy were given in this study. Beam energy over 20 MeV may be suitable for a multi-beam injection scheme [7], but needs to be reduced when using a 10-MeV merger [2]. In the remaining space, we present a few snapshots of the ASTRA simulation outputs for the solutions listed in Table 2. These simulations used 28000 particles. The glitch in the longitudinal phase space can be smoothed out by refining simulation parameters. There is a shallow double-minimum emittance oscillation in the 77-pC simulation that results in a much longer final drift.

### CONCLUSION

A simulation study of a 325-MHz NCRF injector shows that low-frequency cw normal-conducting rf guns can be a viable alternative to high-voltage DC guns for driving envisioned ERL-based x-ray sources using cw linacs or quasi-cw linacs with multi-beam injection for significant cost saving. Further improvement in beam quality should still be possible, especially considering that only a beer-can bunch distribution at the cathode was considered in this study. Further feasibility and optimization studies of various components, especially the gun cavity and first solenoid, are necessary to ensure a solid conceptual design.

#### Sources and Injectors

#### T02 - Lepton Sources

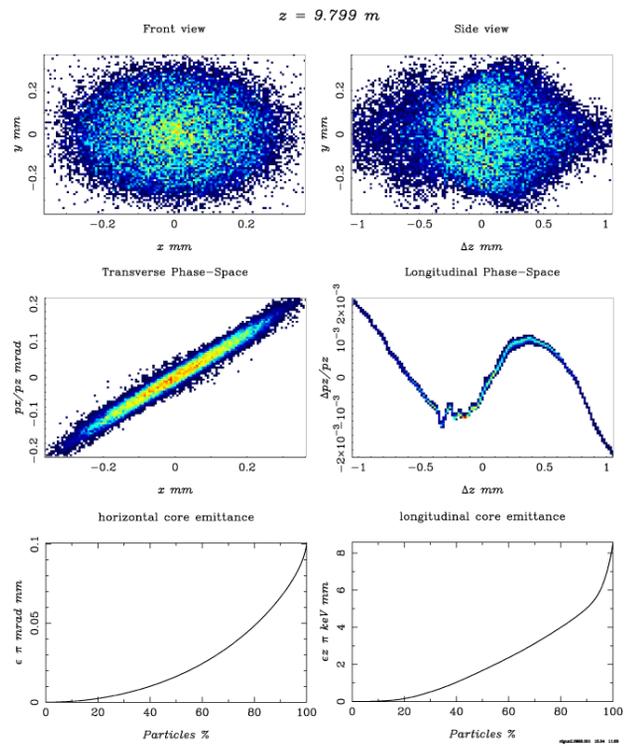


Figure 4: Bunch images at 0.077 nC.

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