

# SIMULATION OF A HIGHER-ORDER MODE RF PHOTOINJECTOR\*

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## Abstract

A photoinjector based on a higher-order mode (HOM) rf cavity presents several potential advantages over traditional photoinjector designs. These include ease of fabrication, tuning stability, and the possibility of achieving higher accelerating gradients. Since the initial proposal [1], the design has evolved towards lower rf power requirements but still maintains the ability to generate very high-quality electron beams.

This paper presents the results of beam dynamics studies on a HOM-based photoinjector roughly equivalent to the SLAC/BNL/UCLA-style 1.6-cell S-band photoinjector [2]. Best-beam property numbers are obtained via simplex optimization, and parameter sensitivity studies are presented. Results are given for idealized as well as typical drive laser profiles.

## 1 INTRODUCTION

The typical 1.6-cell split-type photoinjected rf gun, characterized by the SLAC/BNL/UCLA designs (hereafter referred to as  $\pi$ -mode designs) has proven to be reasonably successful as a generator of high-brightness electron beams. There are some outstanding issues with the general design, however, mainly in the areas of long-pulse and high-gradient operation, and tuning stability over procedures such as cathode changes. In terms of fabrication, also, the design is not simple to construct properly.

Higher-order mode (HOM) cavities provide a potential alternate method for obtaining the rf fields required to generate a high-brightness electron beam. This design style offers a potential for higher gradient operation and easier cooling for long rf pulse operation, as well as easier fabrication and greater immunity to some of the tuning issues associated with the  $\pi$ -mode designs.

This paper considers a design for a HOM-cavity-based photoinjector intended to be, effectively, a drop-in replacement for a standard 1.6-cell  $\pi$ -mode design, with the exception of requiring more rf power. The insertion length, design energy, and required solenoid fields are all very similar. The axial field profile is shown in Figure 1. Unlike the gun design presented in [1], with the exception of the effective field balance, this design is equivalent to a 1.6-cell gun and uses a tapered cell wall to locate the zero-crossing at the appropriate distance from the cathode.

## 2 SIMULATION METHODOLOGY

Four series of simulations were performed; each series consisted of an optimization step, followed by a parameter sensitivity study. The beamline geometry used in all simulations was identical except for the choice of the photoinjector. Each gun was simulated using both an idealized and a more realistic drive laser pulse, for a total of four simulation series; the parameters are given in Table 1.

In the optimization phase, the solenoid current, launch phase, gun gradient, laser beam spot size, and linac phase

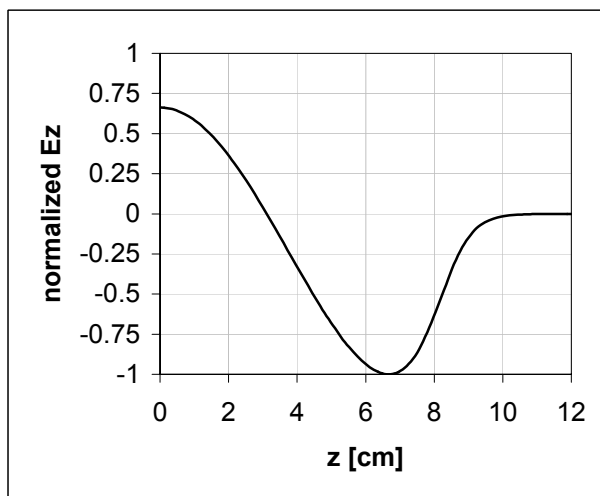


Figure 1: On-axis field profile for the HOM-based gun.

were varied to obtain a good (but not necessarily ideal) starting point for the sensitivity studies. The linac gradient was kept fixed at 7 MV/m. In the sensitivity studies, the gun gradient, laser beam spot size, and solenoid current were varied by  $\pm 5\%$  and the launch and linac phases by  $\pm 5$  deg. This allows a comparison of the two designs

Table 1: Source beam distribution parameters

Source Distribution Parameter [units]	Symbol	Idealized	Realistic
Charge [nC]	Q	1	0.3
Long. distribution		uniform	Gaussian
rms bunch length [ps]	$\sigma_r$	2.808	1.38
Total bunch length [ps]	$L_b$	10	10
Radial distribution		uniform	Gaussian
Sigma beam radius [mm]	$\sigma_r$	n/a	(optimized)
Max. beam radius	$r_{cut}$	(optimized)	$1 \cdot \sigma_r$

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not only in terms of performance at a given operating point, but also in terms of parameter dependence about that point.

PARMELA v3.11, run using 2-d space charge, was used for all simulations. The optimization stage was typically carried out with  $10^4$  particles. The sensitivity studies were run with  $2.5 \cdot 10^4$  particles, and a finer space-charge mesh. Thermal emittance was not included in any simulation.

The basic beamline geometry is shown in Figure 2. The layout shown here is characteristic of a number of installations, including the Advanced Photon Source linac, the Gun Test Facility (GTF) at SLAC/SSRL, and the Accelerator Test Facility (ATF) at Brookhaven National Laboratory. For these simulations, the linac is followed by a 2-m drift distance; the beam properties are calculated at the end of this drift space. In the physical systems mentioned there is no bucking coil pack; it is included in the simulation for ease of modeling.

### 3 OPTIMIZED PARAMETERS

The results of the parameter optimizations are shown in Table 2. The performance of the HOM-based gun is very similar to that of the  $\pi$ -mode design. The  $\pi$ -mode design shows slightly better emittance with an idealized drive laser beam, the HOM-based design slightly better with a more realistic beam. Given additional cavity geometry optimization, the performance of the HOM gun can probably be further improved. As one would expect, there are no dramatic differences in the requirements for solenoid strength, laser spot size, etc.

### 4 SENSITIVITY SCANS

As mentioned above, the intent of the initial optimization

Table 2: Beam properties for optimized injector parameters

	Symbol	Ideal Beam (1 nC)		Realistic Beam (0.3 nC)	
		$\pi$ -mode	HOM	$\pi$ -mode	HOM
Beam Property [units]					
Norm. emit. [ $\mu\text{m}$ ]	$\epsilon_n$	0.55	0.74	0.61	0.62
Spot size [mm]	$\sigma_x, \sigma_y$	0.70	0.96	0.62	0.66
Energy spread [%]	$\sigma_\delta$	0.60	1.0	0.23	0.2
Bunch length [ps]	$\sigma_\tau$	2.8	3.2	1.4	1.8
Gun exit kinetic energy [MeV]		6.36	5.67	6.39	5.46
Optimized Parameter					
Launch phase [deg]	$\phi_{\text{launch}}$	36.1	40.0	22.9	29.0
Sol. current [A]	$I_{\text{sol}}$	170.47	146.37	173.6	144.0
Cath. radius [mm]	$\sigma_r$	(n/a)	(n/a)	0.87	0.92
	$\rho_{\text{cut}}$	0.133	0.150	0.87	0.92
Linac phase [deg]	$\phi_{\text{linac}}$	-37.5	-42.0	-28.8	-46.2
Gun grad. [MV/m]		54.77	51.1	56.0	48.8

tion was not so much to generate the most optimized operating point, but rather to find a good location for the sensitivity studies. For this reason, and for the increased resolution (i.e., increased space-charge mesh density and number of particles) used in the sensitivity scans, the optimal points determined above might not exactly correspond to the optimal values found during the parameter scans.

Figures 3 through 5 show the dependence of emittance from the higher-mode gun upon the solenoid field strength, gun gradient, and beam launch phase, respectively. (The emittance was not found to be strongly dependent upon the capture linac section phase, or laser

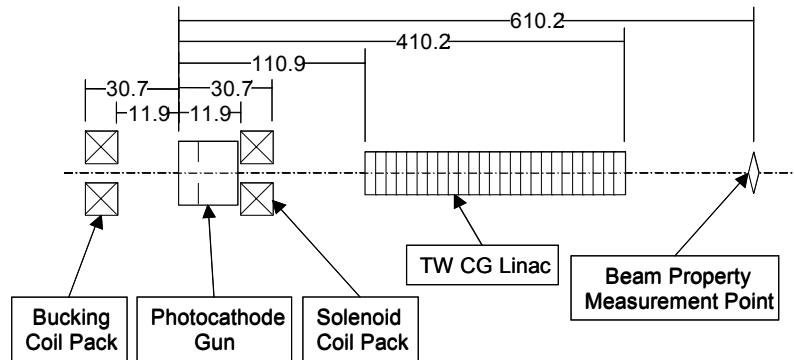


Figure 2: Model beamline layout. All dimensions are in cm.

beam spot size on the cathode.) Close to the minimum emittance the parameter dependence is approximately parabolic; Table 3 lists the second derivative of the dependence curves close to the minimum. This is, effectively, a measure of the sensitivity of the system to jitter in a given parameter. The values were calculated by performing a 2<sup>nd</sup>-order polynomial fit to the data, and eliminating points away from the minimum until a reasonable "local" fit was obtained.

Due to space constraints only the parameter dependencies of emittance are presented here;

however, once the simulations are completed it is very easy to perform the same calculation for other beam parameters, e.g., energy spread or transverse beam spot size.

### 5 DISCUSSION AND CONCLUSIONS

The performance of the HOM-based rf gun appears to be equivalent to that of the standard  $\pi$ -mode photoinjector design in many respects. Indeed, in terms of final emittance generated, the differences are probably within the resolution of the simulation. There appear to be no intrinsic reasons why the design should not perform as expected.

The differences in beam dynamics

will arise mostly from the on-axis field strength ratio of about  $\frac{3}{4}$  between the “cathode” and “full” cells in the HOM-type design, compared to a 1:1 ratio in the normal  $\pi$ -mode design. This is not such a serious issue, however, as the field “balance” in the HOM-based design is fundamentally stable.

In conclusion, although the current simulated performance for the HOM-based design already compares favorably to expectations for existing design, there are clearly more variables that can be included in the optimization; these include the gun geometry itself. The higher-mode design, although requiring approximately twice the power of a comparable  $\pi$ -mode gun, offers advantages in terms of ease of construction, tuning, cooling, pumping, and operating stability.

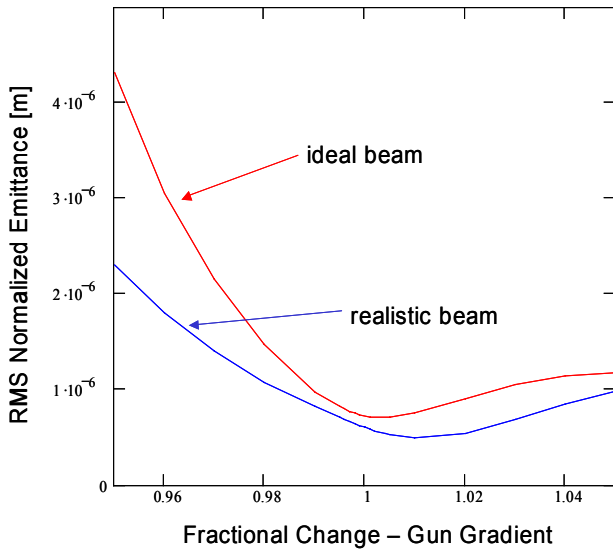


Figure 3: Normalized rms emittance as a function of fractional change in higher-order mode gun gradient.

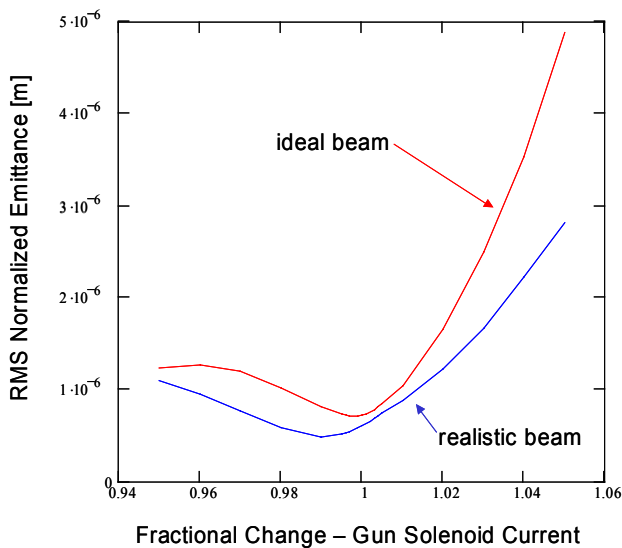


Figure 4: Normalized rms emittance as a function of fractional change in higher-order mode gun solenoid strength.

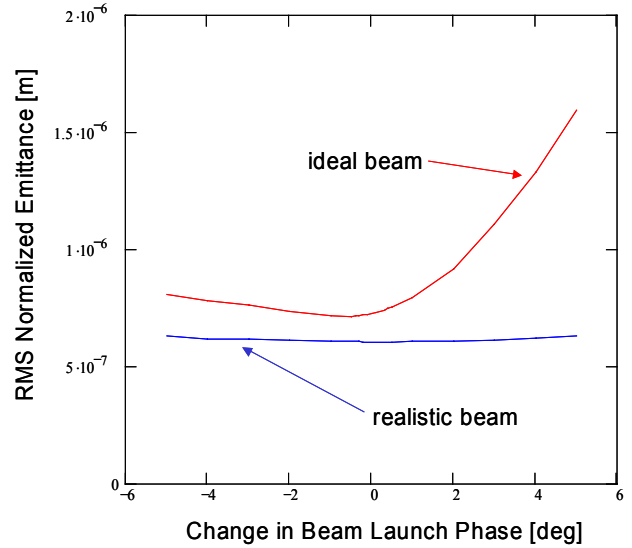


Figure 5: Normalized rms emittance from the higher-order mode gun as a function of change in beam launch phase.

Table 3:  $d^2\epsilon_n/d(\text{variable})^2$  for gun gradient and solenoid (fractional changes), and launch phase (in radians)

Parameter	Derivative w.r.t. <sup>‡</sup>	“Ideal” beam	“Realistic” beam
Gun gradient	$E_z/E_{z_0}$	0.14 $\mu\text{m}/\% ^2$	0.07 $\mu\text{m}/\% ^2$
Gun solenoid	$I_{sol}/I_{sol_0}$	0.18 $\mu\text{m}/\% ^2$	0.07 $\mu\text{m}/\% ^2$
Launch phase	$\phi_{\text{launch}}$	0.02 $\mu\text{m}/\text{deg}^2$	0.005 $\mu\text{m}/\text{deg}^2$

<sup>‡</sup>  $E_z$  is the on-axis peak rf field strength,  $I_{sol}$  is the solenoid current,  $\phi_{\text{launch}}$  references the bunch centroid. Subscript “o” refers to the optimized value.

## 6 ACKNOWLEDGEMENTS

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## REFERENCES

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