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Publication Date
2002-05-22

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A HIGH-GRADIENT HIGH-DUTY-FACTOR RF PHOTO-CATHODE ELECTRON GUN*

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Abstract

We describe the analysis and preliminary design of a high-gradient, high-duty factor RF photocathode gun. The gun is designed to operate at high repetition rate or CW, with high gradient on the cathode surface to minimize emittance growth due to space charge forces at high bunch charge. The gun may also be operated in a solenoidal magnetic field for emittance compensation. The design is intended for use in short-pulse, high-charge, and high-repetition rate applications such as linac based X-ray sources. We present and compare the results of gun simulations using different codes, as well as RF and thermal analysis of the structure.

1 INTRODUCTION

Pillbox photocathode RF guns have proven very successful at producing high intensity low emittance beams for free electron lasers and other experiments [1]. We present a reentrant design that has been developed for high duty factor operation that might be useful for future high pulse rate accelerators or light sources. The choice of shape increases efficiency compared to pillbox designs, which is important in maximizing the accelerating field. The reentrant gun cell may be followed by one or more standard cells and be used with emittance compensation solenoids, see figure 1.

Thermal performance of the structure has been analyzed numerically using ANSYS [2].

The gun has been simulated in 2D using the MAFIA PIC code TS2 [3], and PARMELA [4]. Studies are underway using HOMDYN [5], to get a third perspective. Each code has some method of space charge calculation. MAFIA claims to have the most detailed physical model with complete field maps and full PIC implementation of the particle evolution, but is the slowest to run. PARMELA and HOMDYN run faster but introduce some simplifications in the space charge calculation or field mapping. All of the codes can include solenoid fields.

2 CELL SHAPE

The reentrant gun cell shape, figure 2, is chosen to maximize the shunt impedance and therefore the efficiency. Initial estimates suggested that a field of up to 64 MV/m on the cathode could be supported at an operating frequency of 1.3 GHz without dissipating an unacceptable amount of power in the cavity walls. This is about twice the Kilpatrick value at this frequency.

* This work was supported by the U.S. Department of Energy under contract DE-AC03-76SF00098.
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The cavity gap was chosen so that a bunch launched on the crest of the RF cycle (defined as 90° in figure 3), could exit the cavity at the next zero crossing. Bunches launched at any phase before crest down to zero crossing (0°), would still exit the gun within the accelerating half cycle with reasonable energy, figure 3.

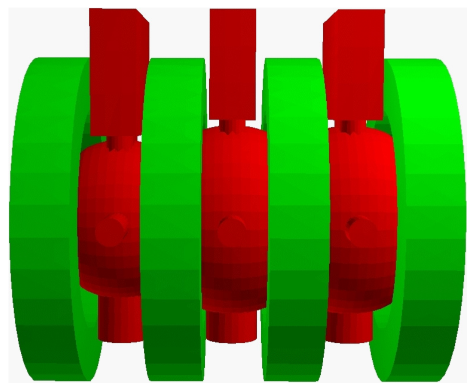

Figure 1. Solid model of proposed three-cell RF gun with solenoid compensation coils and power couplers.

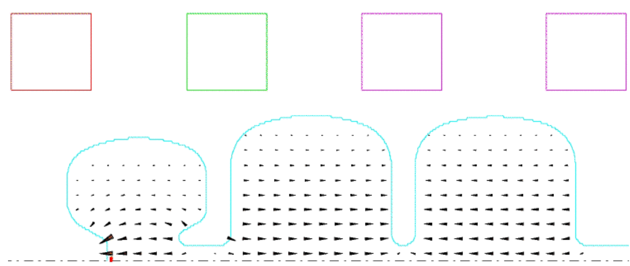

Figure 2. Profile of 3-cell RF gun showing MAFIA calculated electric fields and position of solenoid coils.

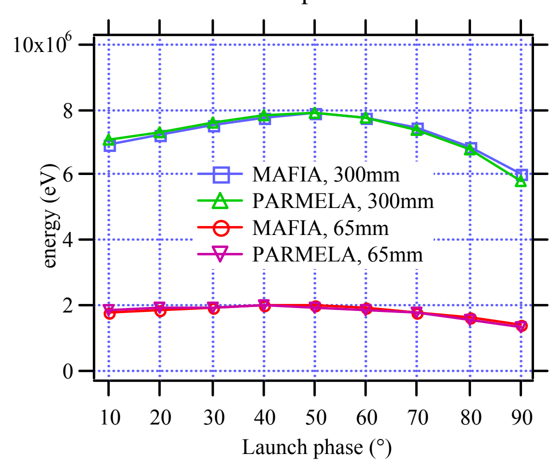

Figure 3. Variation of bunch energy with launch phase, 64 MV/m on cathode, 43 MV/m cells 2 & 3,π mode.

A short drift tube is used to isolate the gun cell from the next accelerating cell. The gun cell is independently powered and phased. The outer part of the cavity is generously rounded to minimize the wall power density and the central section is spherical to simplify the machining of tuner and coupler ports. The second and third cells are fairly conventional but are run at maximum accelerating gradient.

3 BEAM DYNAMICS

The gun was simulated in each of the codes for a range of operating parameters. For simplicity the bunches are assumed to have rectangular profiles both in radius and in time, with uniform charge density, and are launched with zero thermal emittance. The spot size on the cathode had a radius of 2mm. The peak field on the cathode was 64 MV/m while the field on axis in cells 2 and 3 was 43 MV/m. The bunch parameters were recorded after the first cell (z = 65mm), and at the exit of the gun (z = 300mm).

Table 1: Nominal operating parameters

	Gun cell	Cell 2 & 3
Frequency	1.3 GHz	1.3 GHz
Rep. rate	10 kHz	10 kHz
Duty factor	~5%	~5%
E_o	64 MV/m	43 MV/m
P_{peak}	581 kW	1550 kW
$P_{average}$	29 kW	77.5 kW
$P_{dens\ max}$	110 W/cm^2	107 W/cm^2

3.1 Space-charge effects

To study the effects of space charge the parameters were varied in two ways. First the charge within the bunch was varied from 1 pC up to 1 nC keeping all other parameters fixed. Figure 4 shows how the normalized transverse emittance varied, indicating a clear blow up at high charge as expected. MAFIA and PARMELA agree quite well at 65 mm but differ at 300 mm. MAFIA and PARMELA results both showed some blow up in the longitudinal emittance at 65 mm for high charge per bunch but disagreed on the absolute values and were inconsistent at 300 mm for reasons which are not yet understood.

The other method kept the charge fixed at 1 nC and varied the bunch length from 10 ps to 40 ps, thus reducing the charge density by up to a factor of four. Figure 5 shows how the transverse emittance from MAFIA varied over this range. Clearly there is less sensitivity to charge density in this case. The longitudinal emittance actually worsens as the bunch length is increased, suggesting that other effects such as energy spread from the large phase range may be more significant than space charge.

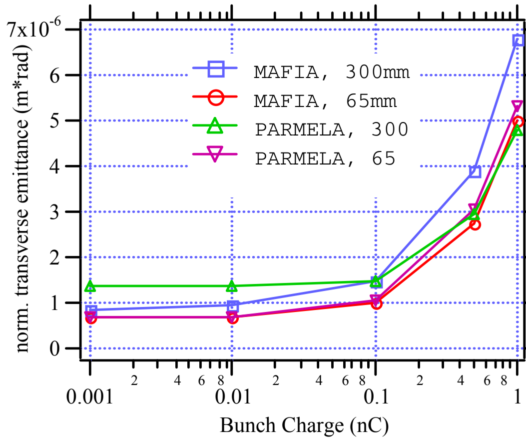

Figure 4. Variation of normalized transverse emittance with bunch charge, 64 MV/m on cathode, 60° launch phase, 10 ps bunch length, 43 MV/m for cells 2 and 3.

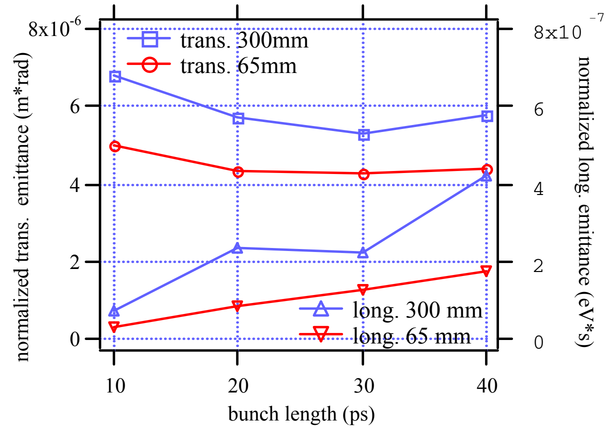

Figure 5. Variation of normalized transverse emittance with bunch length, 64 MV/m on cathode, 60° launch phase, 1 nC charge, 43 MV/m for cells 2 and 3.

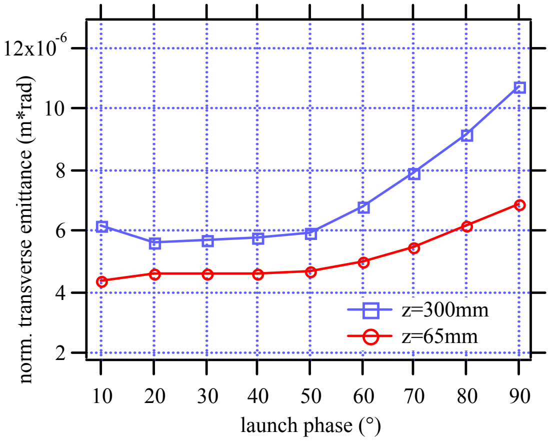

Figure 6. Variation of normalized transverse emittance with launch phase, 64 MV/m on cathode, 1 nC, 10 ps bunch length, 43 MV/m for cells 2 and 3 (MAFIA).

3.2 Launch phase

Another important parameter in the gun dynamics is the phase of the RF cycle at which the bunch is launched from the cathode. To study this the simulations were run with launch phases from 10° to 90° with all other parameters fixed, see figure 6. The optimum appears to be well ahead of crest. This may indicate that RF focusing is at least as important as accelerating field at the cathode.

Simulations show a similar trend in the longitudinal emittance after the first cell, although the codes differ on the final number. Bunching due to the slope of the RF waveform may be compensating for longitudinal space charge forces at low phase angle. The calculated longitudinal emittance leaving the third cell doesn't show a clear trend, however no attempt was made to optimize the phasing of cells 2 and 3 for different launch phases.

3.3 Phase offset between first and second cells

Introduction of the short drift between the gun cell and the subsequent accelerating cells introduces a small timing offset. This can be compensated by retarding the downstream cells by about 30°, however simulations indicate that apart from a small increase in the energy there is not much effect on the output beam parameters when this is added.

3.4 Solenoid compensation of emittance

A static magnetic field can be superimposed on the RF fields in all of the codes. In some applications, for example where a flat beam transformation is envisioned downstream of the gun, it may be necessary to have a finite magnetic field at the cathode. Figure 7 shows how a solenoid field may help counteract emittance growth in the gun. PARMELA and HOMDYN are better able to study this as they can model extended beam lines.

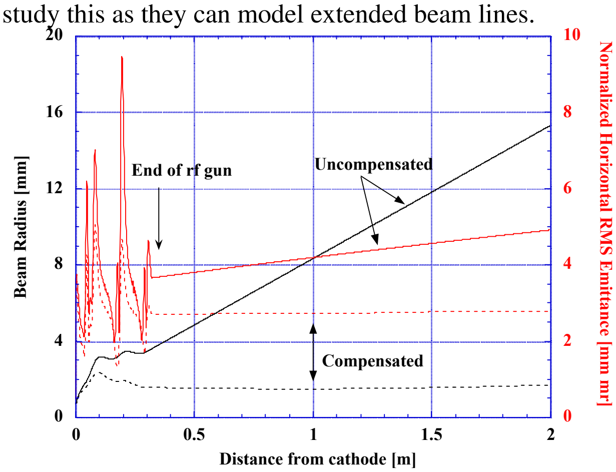

Figure 7. Effect of solenoid compensation (HOMDYN)

4 THERMAL ANALYSIS

A preliminary analysis of the gun indicates that the fields in table 1 should be sustainable at 5% duty factor. Figures 8 and 9 show the RF field and temperature distributions calculated by ANSYS for the gun. For CW operation the standard cells may be limited to ~13 MV/m but the gun cell should be able to provide ~20 MV/m. This case has not yet been studied in detail. Extra standard cells could be added to restore the exit energy.

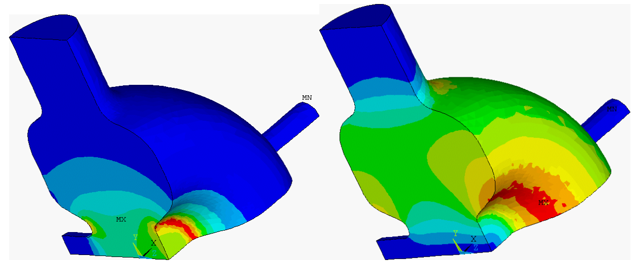

Figure 8. Surface E and H fields from ANSYS

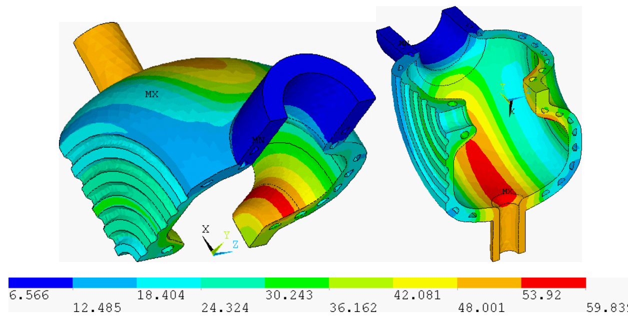

Figure 9. Temperature calculated by ANSYS

5 CONCLUSIONS

There is generally good agreement between the codes on the overall gun performance, though they differ in detail. The calculated performance of the gun is good enough for many applications and close to that required for the next generation of high repetition rate light sources. With solenoid compensation the emittance may be good enough, although there is scope for further optimization. The fields assumed appear to be obtainable with a repetition rate as high as 10 kHz. At bunch repetition rates higher than the fill time the structure essentially runs CW. The fields in the standard cells would be reduced to approximately 13 MV/m, but in the gun cell the fields could be sustained at about 20 MV/m CW.

6 REFERENCES

[1] "RF photoinjectors", P.G.,O'Shea, Proceedings of 2nd Advanced Accelerator Workshop on the Physics of High Brightness Beams, Los Angeles, CA, USA, 9-12 Nov. 1999.) Singapore: World Scientific, 2000. p.17-26.

[2] http://www.ansys.com/

[3] http://www.cst.de/

[4] Lloyd M. Young, James H Billen, "PARMELA", LANL,LA-UR-96-1835, Revised May 21. 2002

[5] M. Ferrario, et. al., "Multi-bunch energy spread induced by beam loading in a standing wave structure", Part. Accel. 52, 1 (1996).