DESIGN OF AN X-BAND PHOTOINJECTOR OPERATING AT 1 kHz *

W.S. Graves†, A.C. Goodrich, M.R. Holl, and N.J. O'Brien, Arizona State University, Tempe, USA
V. Bharadwaj and P. Borchard, Tibaray Inc., Stanford, USA
V. Dolgashev, E.A. Nanni, SLAC, Menlo Park, USA

Abstract

A kHz repetition rate RF photoinjector with novel features has been designed for the ASU CXLS project. The photoinjector consists of a 9.3 GHz 4.5 cell standing-wave RF cavity that is constructed from 2 halves. The halves are brazed together, with the braze joint bisecting the irises and cells, greatly simplifying its construction. The cathode is brazed onto this assembly. RF power is coupled into the cavity through inline circular waveguide using a demountable TM01 mode launcher. The mode launcher feeds the power through 4 ports distributed azimuthally to eliminate both dipole and quadrupole field distortions. The brazed-in cathode and absence of complex power coupler result in a very inexpensive yet high performance device. The clean design allows the RF cavity to sit entirely within the solenoid assembly. The cathode gradient is 120 MV/m at 3 MW of input power. The cathode cell is just 0.17 RF wavelength so that laser arrival phase for peak acceleration is 70 degrees from zero crossing resulting in exit energy of 4 MeV. The photoinjector will operate with 1 μs pulses at 1 kHz, dissipating 3 kW of heat. Details of the design are presented.

INTRODUCTION

The ASU Compact X-ray Light Source (CXLS) includes x-band accelerator structures designed to operate at 1 kHz repetition rate to produce high intensity, sub-picosecond hard x-ray pulses with flux up to 1E8 photons/shot or 1E11 photons/second. The CXLS is being developed from a previous effort [1] at MIT and has similar performance. The electron beam is produced by a photoinjector with a number of novel features. All of the accelerator structures operate at 9.3 GHz RF frequency.

The major parts of the photoinjector are 1) RF gun consisting of a four and a half cell standing wave cavity, 2) TM01 mode launcher that serves as a demountable RF coupler to the gun, and 3) solenoid magnet into which the RF gun is fully inserted. The RF gun photocathode is brazed to the RF cells with no provision for its replacement. In this scheme, if the cathode is damaged the entire gun cavity can be quickly and inexpensively replaced. Figure 1 is a cut-away view of the overall photoinjector showing the gun, mode launcher and solenoid. The cathode is at the center of the solenoid magnet, which has 2 equal coils in a bucking configuration to zero the magnetic field at the cathode. The solenoid and gun are separately mounted and can be independently aligned in all dimensions. In the following sections we describe the electrical, thermal, and mechanical design of the photoinjector.

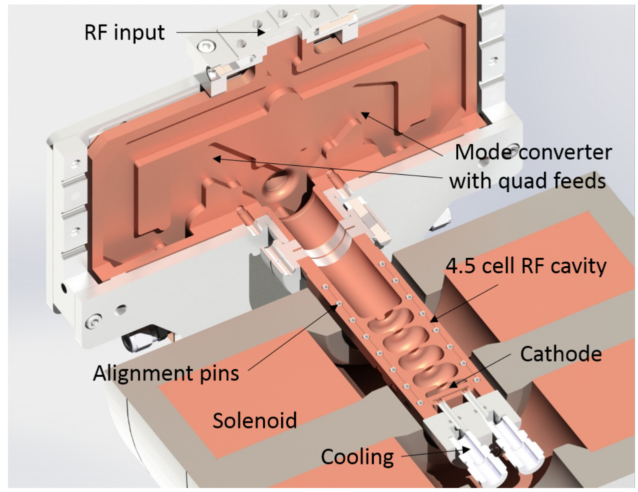

Figure 1: Cutaway view of photoinjector assembly including mode launcher with quadrupole symmetry, 4.5 cell RF gun, and solenoid magnet.

RF ELECTRICAL DESIGN

Designs were tested with 2.5, 3.5, and 4.5 cells eventually resulting in the current 4.5 cell design. The longer gun distributes the fields over a larger area reducing thermal loading, and results in a higher beam exit energy for a given RF power. The penalty is a reduced cathode field compared to shorter designs. However the cathode field is still a robust 120 MV/m at 3 MW peak power.

In the first step of the cavity design process, the gun was simulated with the eigensolver of the 2D finite element code SLANS [2]. In order to achieve high RF efficiency, the gun has a relatively small aperture and thus relatively small coupling between cells. The power propagating from the gun exit toward the cathode results in phase shifts among the cells that must be properly accounted for in the beam dynamics simulations. Therefore, the calculations of the fields to be used in beam dynamics simulations were done with the driven module of HFSS. The magnitude, real and imaginary parts of complex on-axis electric field and its phase are shown in Figure 2. The only true standing wave cavity in this design is the cathode cell. Fill time of the cavity is 156 ns for the estimated Q-loaded of 4562.

The cathode "half cell" is significantly shorter than $\lambda_{RF}/4$ to account for phase slip after beam launch and to allow for cancellation of energy chirp. The cathode cell length was set to achieve maximum energy gain of 4.0 MeV for initial

* This work funded by Arizona State University.
† wsg@asu.edu

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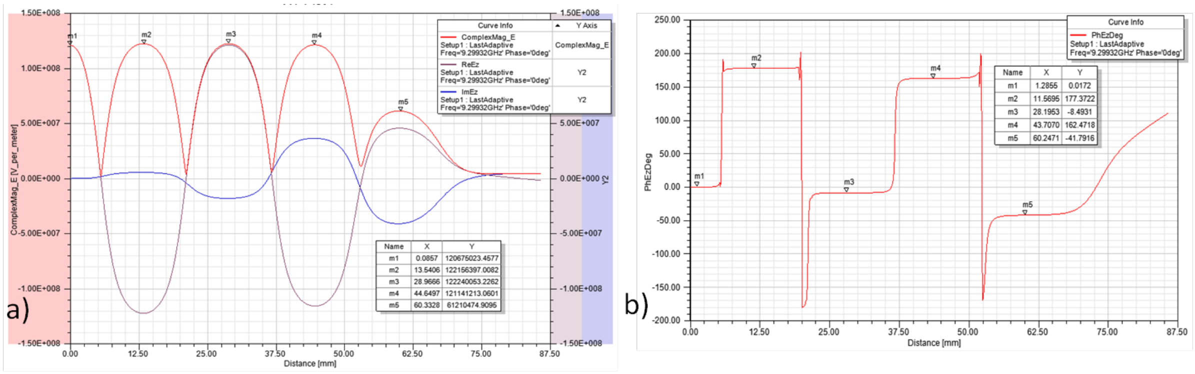

Figure 2: On-axis electric fields calculated by HFSS simulations for 4.5 cell 9.3 GHz gun, fields normalized to 3 MW of lost rf power and rf phase is set to have only a real field on the cathode. The cathode is located at zero coordinate of the horizontal axis; a) magnitide, real and imaginary part of electric fields with peak cathode field 120 MV/m, fields in the cathode cell and next 3 cells are balanced within +-1%; b) complex phase of the electric fields showing phase slippage between coupler and the cathode cell of 42 degrees.

phase of 70 degrees from zero crossing. Setting the launch phase to 70 degrees rather than 90 degrees where the field is maximum helps to separate the photocurrent from dark current (field emission) which primarily occurs close to 90 degrees. The downstream beam optics then filter the dark current since it is at the wrong energy for transport.

The gun is designed to operate at an unprecedented high average power of 3 kW. Given this, the design of the cooling circuit will result in slightly different average temperatures in each cell. We used the average temperatures and distorted cavity shapes found from Ansys thermal and mechanical modeling to recalculate the complex on-axis electric fields for the distorted gun. The results of simulation show that at full average power of 3 kW the change of the gun reflection would be barely detectable. The change in amplitude of the on-axis fields is a small perturbation of the Re(Ez) in comparison with change of the same Re(Ez) due to the phase slippage. Furthermore the high power leads to azimuthally nonuniform temperatures and thus distorted cell radii. After optimization the distortion of the cell walls is mostly quadrupole, with total volume about 10 times smaller than that from a typical tuning bump, which can change cell frequency by 5 MHz. As a result the effect on the beam dynamics of this small azimuthal distortion of the cavity walls is also negligibly small.

THERMO-MECHANICAL DESIGN

The RF gun utilizes the recently demonstrated approach [3] of splitting the accelerator cell structure by splitting along the midplane and subsequently joining them using a high temperature copper-gold brazing process with the two sections aligned by precision pins. The split section approach reduces part count and enhances flexibility of coolant layout compared to a conventional accelerator structure of axially stacked cups.

The thermal performance of the RF gun was optimized using ANSYS Fluent CFD analysis. Slots were utilized in the first three irises to remove heat from the irises and reduce stresses in the copper cell walls. The structure features three separate cooling circuits to deal effectively with the 3 kW average power in a small volume. The 3 circuits include one cathode cooling circuit and one cooling circuit for each of the split halves.

With an inlet temperature of 300 K and an average power loading of 3 kW, the gun structure reaches a maximum temperature of 332 K (Figure 3). Due to the optimized cooling configuration the temperature distribution across the cells remains fairly uniform with a maximum variation of approximately 15 K. The temperature rise of the cathode surface is 27 K. The temperature variations within cells are less than 8 K and the variation of average temperature between cells is below 5 K. The results of the thermal analysis were used to perform a stress analysis; the peak stress is 35 MPa at iris 1 which ensures that the annealed copper remains in the elastic regime. To investigate the effect of the pulse RF heating of the cell structure a 3D ANSYS thermal analysis was performed. The peak pulse surface heating is 23 K for a 3 MW 1.1 µs pulse length. Properties of the photoinjector are summarized in Table 1.

The final RF gun assembly consists of the RF gun structure and the mode launcher. A commercial gate valve is mounted to the assembly using a standard 2.75 inch conflat flange and associated vacuum hardware. For the interface between the RF gun and mode launcher a RF vacuum flange and gasket has been designed which provides a UHV joint while minimizing any effects on the RF entering the gun structure. The mode launcher [4] forms the main structural element; it features a stainless steel exoskeleton structure which forms a rigid backbone for the assembly.

The RF gun is a brazed assembly which consists of the two split halves forming the cell structure which are aligned using precision alignment elements, an RF flange, a number of brazed-in push-pull tuning pins and cooling covers and tubes. The mode launcher is a brazed assembly with a copper waveguide feed network; a WR-90 RF input flange, a ConFlat downstream vacuum flange and an upstream RF vacuum

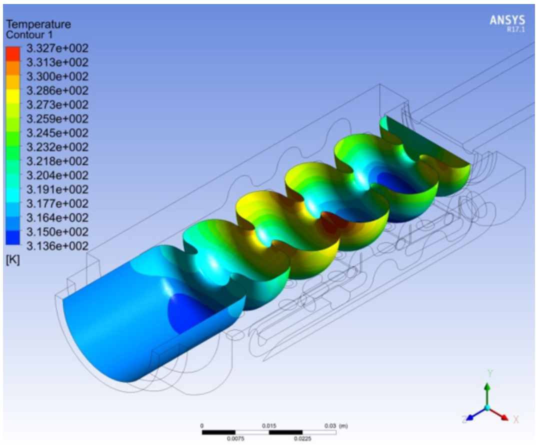

Figure 3: Temperature (K) of RF gun structure with coolant inlet temperature 300 K. Maximum average temperature rise is 32 K and maximum pulsed heating is 23 K.

flange. The stainless steel frame plates are brazed to the copper structure in the area around the beam axis and free floating around the perimeter to minimize deformation in the structure due to the thermal expansion difference the two materials. After braze the two facing stainless steel plates will be bolted together using support blocks. The upstream and downstream beam pipes feature a copper core with an outer stainless steel sleeve for mechanical support.

SOLENOID MAGNET

The solenoid magnet shown in Figure 1 is configured as an iron yoke surrounding two equal and opposite bucking coils that provide a B=0 plane at the magnet center. The RF gun is inserted so that the cathode is located at this plane. The main coils are both powered by a single power supply. A small bipolar power supply will be floated on one coil to adjust the zero field location. The field rises rapidly along the longitudinal axis to a peak value of 4900 Gauss at z = 5.8 cm at approximately the exit of the last RF cell. The effective magnetic length is 5.3 cm. The fast rise of the field near the cathode, strong B-field, and short magnetic length all contribute to a high quality lens and bright beam production. The lens captures the rapidly expanding electron beam, arresting time-dependent twists in the phase space ellipses before they show much betatron phase advance. The solenoid bore has a 5.5 cm diameter to accommodate the RF gun. The solenoid and the RF gun are not physically attached so that each can be separately aligned. The solenoid mounting apparatus allows the solenoid to slide backwards so that the gun can be simply dismounted and replaced from its attached RF mode launcher. The total solenoid length is 22 cm with a diameter of 28 cm. The coil current density is 5.9 A/mm^2. The solenoid design was optimized to move the lens position to the gun exit and lengthen the solenoid to reduce its geometric aberration. The solenoid power supply will be sized for a factor of 50% higher current than nominal to allow operation at higher bunch charge and for solenoid emittance scans. The power supply is expected to have 10 PPM stability with feedback from a DC current transformer. At the nominal operating point, the peak flux is about 1.4 T in the main yoke and 1.6 T in the nose cones.

Table 1: ASU CXLS Photoinjector Specifications

Parameter	**Value**	**Units**
RF frequency	9300.0	MHz
Nearest mode	9294.4	MHz
Cathode gradient	120	MV/m
Exit energy	4.0	MeV
Field balance	1:1:1:1:0.5	
Q factor	9124	
Q loaded	4562	
Stored energy	0.47	J
Max surface Efld	136	MV/m
Max surface Bfld	232	kA/m
Cathode cell length	0.17	λ_{RF}
Peak power	3	MW
RF pulse length	1.0	µs
Repetition rate	1	kHz
Average power	3	kW
Average temp rise	32	K
Pulse temp rise	23	K
Max stress	35	MPa
Solenoid Bfld	0.49	T
Solenoid length	54.6	mm

CONCLUSIONS

A new 4.5 cell RF photoinjector has been designed with novel features including operation with high gradient of 120 MV/m on cathode at 1 kHz repetition rate, highly efficient cell shape requiring just 3 MW peak power to generate this high gradient and high exit energy of 4.0 MeV, split-half construction to simplify parts manufacture and allow better cooling channel design, on-axis RF feed through a demountable TM01 mode launcher that is separate from the RF cavity, and a solenoid magnet that completely encloses the RF cavity for improved beam dynamics. This photoinjector will be used to produce electron beam for the ASU Compact X-ray Light Source.

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