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ABSTRACT

The proposed UV-FEL user's facility at Brookhaven National Laboratory will require a photocathode gun capable of producing short (< 6 psec) bunches of electrons at high repetition rates (5 kHz), low energy spread (< 1.5 %), a peak current of 300 A (after compression) and a total bunch charge of up to 2 nC. At the highest charge the normalized transverse emittance should be less than 7π mm-mrad. We are presently designing a gun that is expected to exceed these requirements. This gun will consist of $3\frac{1}{2}$ cells, constructed of GlidCop-15, an aluminum oxide dispersion strengthened copper alloy. The gun will be capable of operating at duty factors in excess of 1%. Extensive beam dynamics studies of the gun were used to determine the effect of varying the length of the first cell, shaping the apertures between cells, and increasing the number of cells. In addition, a detailed thermal and mechanical study of the gun was performed to ensure that the thermal stresses were well within the allowable limits and that copper erosion of the water channels would not occur.

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MASTER

1. INTRODUCTION

The free-electron laser (FEL) offers the opportunity of providing high power coherent radiation sources in regions presently unattainable by conventional atomic and molecular lasers. For this reason, it has been proposed to build an ultraviolet FEL user's facility[1] capable of producing radiation between 75 - 300 nm at a repetition rate of 5 kHz. Though the superconducting linear accelerator for this facility is considered to be proven technology, the RF photocathode gun would be operating in a regime undemonstrated at this time. The gun would be required to produce 2 pulses separated by 10 ns every 200 μ sec. The emittance of the electron bunches is required to be below 7π mm-mrad (normalized RMS) with peak currents of 300 A after compression. The RF filling times of these guns are on the order of 1 - 2 μ sec, thus the RF duty factor would be nearly 1%.

Design and construction of such a gun (Gun II) has begun under a joint Grumman-Brookhaven National Laboratory (BNL) research collaboration. The starting point for our design is the present $1\frac{1}{2}$ cell BNL photocathode RF gun (Gun I) shown in Fig. 1. The beam dynamics of the gun are modeled with the PARMELA[2] and MAGIC[3] particle codes. These codes are used to study the emittance growth of the electron bunch as it is accelerated through the gun, as well as to determine how the operational parameters effect its characteristics (i.e. divergence, momentum spread, energy, current).

The thermal and mechanical properties of the gun were modeled with the ANSYS[4] finite element code. Power deposition profiles were calculated with SUPERFISH.[5] A thermal/structural analysis was performed to determine the temperature profiles and the pressure and thermally induced stresses. The Von Mises (equivalent) [6] Stress Criteria was used to determine stress level margins.

2. BEAM DYNAMICS MODELING

The majority of the beam dynamics modeling was done with the MAGIC particle-in-cell code. This code includes the effect of image currents, space charge, and wakefields. The

axisymmetric gun geometry (2-D) was modelled with the exact gun fields. This is accomplished by prescribing the magnetic field for the fundamental TM_{01} cylindrical cavity mode and allowing the cavity to ring while numerically damping out higher order modes. The ratios of the electric and magnetic fields are compared at various times to verify that the higher order modes are greater than 60 db down from the fundamental mode. The fields are then stored and used for later runs with particles. The damping of higher order modes is turned off for the particle runs. Figure 2 shows a vector plot of the electric fields for a $3\frac{1}{2}$ cell gun.

The advantage of using the MAGIC codes is that the field components at the cavity apertures and beam exit are continuous and the method of calculating the space charge forces is inherently more stable. To properly resolve the electric fields of the electron bunch near the cathode, where they are rapidly accelerated, the numerical grid for calculating the fields is made very fine near $Z, R = 0$. In addition, the time steps are small enough to avoid plasma frequency and grid type instabilities, and to properly resolve the temporal behavior of the wakefields.[7] Typical simulations for a $3\frac{1}{2}$ cell gun consisted of a grid 2000×90 ($Z \times R$), 1500 particles, and required nearly 6 hours of computer time (Stardent 3000). Particles are emitted in nearly any functional form in radius and time to model the laser illumination of the cathode. Figure 3 shows contours of the wake field created by the bunch as it is accelerated through the gun.

The majority of our simulations used Gaussian profiles with a temporal extent of $\pm 2\sigma_t$ ($\sigma_t = 2$ psec), and a radial extent of $1\sigma_r$ ($\sim 1 - 5$ mm). Table 1 lists the operational parameters for Gun II. Statistics of the particles are tracked through the length of the gun. Figure 4. shows the emittance (calculated from the mechanical momentum), divergence, momentum and momentum spread through the gun. The emitted electron bunch could be modeled as initial cold ($\epsilon_n = 0$), or thermalized (by an amount equal to the difference between the photon energy of the laser and the work function of the cathode material). The most recent experiments at BNL[8] have utilized a copper photocathode whose work function is better matched to the photon energy of the laser than the previous Yttrium cathode. The thermal energy for electrons emitted from the Cu cathode is 0.4 eV versus 1.5 eV for the Yt cathode. To improve the resolution of space charge and RF emittance

contributions, the particles were emitted cold in the majority of our simulations. Emittance values are always reported with the addition (in quadrature) of the thermal emittance.

Most of our simulations were done for a $1\frac{1}{2}$ cell gun since they require $\frac{1}{4}$ of the computer time and uncover most of the underlying physics. A number of aspects of the gun design were investigated: temporal and spatial laser illumination profile shaping; total charge; electric field strength; launch phase; field tilt; aperture shaping; and the length of the first cell. The brightness, B , was used as one figure of merit for our gun design. We use the definition:

$$B = \frac{I}{\epsilon_n^2}, \quad I = \frac{Q}{\sqrt{2\pi} \sigma_b},$$

where I is the peak current, ϵ_n is the RMS invariant emittance, Q is the total charge, and σ_b is the bunch length (divided by the speed of light). After the beam exits the gun, it enters a transport line whose function is to match the beam to the linac. In addition, the transport line may serve to magnetically compress the bunch length, resulting in peak currents >1000 amps. The compression results from differing path lengths for particles of differing momentum in bending magnets. The compressibility was determined analytically and used to determine the ideally compressed current.

The divergence of the beam is inversely proportional to γ , the relativistic factor, and the space charge forces are inversely proportional to γ^2 . Simulations of the full $3\frac{1}{2}$ cell gun show that the addition of 2 full cells for the gun (Gun II) will double the momentum of electrons to 10 MeV/c which should result in a bunch that is more easily transported and compressed. Figure 5 shows the longitudinal phase space (1 nC bunch) at the gun exit ($\sigma_b = 0.55$ mm, $dP/P = 1.5\%$) and after being ideally compressed ($\sigma_b = 0.029$ mm). Figure 6 shows the transverse phase space at the gun exit ($\sigma_x = 3.5$ mm, $\sigma_x' = 8.3$ mrad).

A study was made to determine the effect of varying the length of the half cell on the emittance, divergence and compressibility. It was found that by increasing the length of the half cell from 2.625 cm ($\lambda/4$) to 3.5 cm, the divergence was reduced by 20%, the compressibility increased by a factor of 2, and the effect on the emittance was negligible. The 3.5 cm first cell offers a number of other advantages. The peak electric field is on the cathode rather than on the

aperture as in the previous case. This should allow the cathode field to reach 110 MV/m with the same conditioning that it takes to reach 100 MV/m in the present BNL gun.

For the gun with the longer half cell, minimizing the emittance requires the launch phase to be advanced by 6° for a 1 nC bunch. If one considers the transit time for a relativistic electron bunch, the extra length of the first cell corresponds to 27° of RF phase. However, since the electrons are launched at a lower electric field gradient, the dwell time in the first cell is increased as is the effect of the non-linear transverse electric fields which increase the emittance. As a result, the minimum emittance requires a launch phase advanced by 16° for a 0.1 nC bunch and 6° for a 1 nC bunch.

The smaller phase advance causes the particles to arrive ahead of the zero crossings at the apertures. The final two cells of the gun will have independent phase control which will compensate for the early of the particles. This provides a means of controlling the longitudinal phase space (decreasing the momentum spread or increasing the compressibility), as well as a means for matching the beam to the compression system.

It had been suggested that the transverse non-linear fields at the apertures between cavities could contribute significantly to the emittance of the beam as it passed through the aperture. To reduce the non-linear field components, the aperture can be shaped according to the prescription:[9]

$$r = \sqrt{a^2 - \left(\frac{4d}{\pi}\right)^2 \log\left(\sin \frac{\pi z}{2d}\right)},$$

where a is the aperture radius and d is the length of the cell. We have verified that this prescription does indeed significantly reduce the non-linear transverse fields, but does little to reduce the emittance of the bunch. This results from the fact that most of the emittance growth occurs very close to the cathode where the particle velocities are much less than the speed of light.

Our modeling activities are still continuing to determine the optimal operational parameters. Table 2 summarizes the best modeling results to date. The impact of high compressibility can be

seen when comparing the exponential gain lengths for the UV-FEL[1]. The nearly factor of 5 reduction in wiggler length could significantly reduce the construction costs of such a device.

3. THERMAL AND MECHANICAL DESIGN

Operation at duty factors of 1% present significant challenges in the heat removal aspects of the gun as well as the pressure and thermally induced stresses and deformations. The half cell of the gun will be 3.5 cm long followed by 3 full cells each 5.25 cm ($\lambda/2$) in length. The longer cell simplifies the construction of the gun by reduced the space constraints.

The inner diameter of the half cell is 8.25 cm and it is 8.31 cm for the full cells. The peak power is 12.5 MW, thus an average power of 125 kW must be removed from the structure. Since Gun II will utilize a copper cathode, the cathode wall will be constructed of a solid copper plate without penetrations. The cathode plate, four cylindrical spool pieces and four aperture pieces will be brazed together. Two waveguides are used to power the cavities. The cathode plate is a 0.75 cm long cylinder 12.25 cm in diameter, with coolant channels milled in a circular pattern. A second 0.75 cm long cylinder is brazed on the back to enclose the channels. A 2.5 cm long cylindrical spool piece is used to connect the photocathode to the aperture. The spool pieces for the full cells are 3.25 cm long. All of the spool piece are cooled by circular channel machined into each end. Each aperture is designed as two cylindrical pieces, 1.0 cm long with two coolant channels milled in a circular pattern, which are brazed together. The aperture opening is a separate machining operation.

We have chosen to use GlidCop-15, an aluminum oxide dispersion strengthened copper alloy, which combines good thermal, electrical, and structural properties. The GlidCop will be electroplated with 0.001" of OFHC copper to provide the good electrical conductivity for the cavity and a barrier for the silver based braze alloys.

The thermal/structural analysis entails determining the temperature distributions and the corresponding deformations and stresses imposed on the cavity by the applied RF and laser

loading. The results are evaluated to insure that the design can adequately perform its function and meet the requirements of the ASME Boiler and Pressure Vessel Code.[10]

The Swanson Analysis System, ANSYS, was chosen as the finite element thermal/structural code to perform the evaluation of the design. ANSYS provides 2-D and 3-D modeling capability with thermal and structural elements compatible with the analysis requirements. Steady state and transient analysis with temperature dependent material properties can be performed. It is capable of post-processing the resulting stresses to check compliance with the criteria of the ASME code.

The thermal management of the gun requires heat removal from a cavity only 8.31 cm in diameter with peak power densities of 22 kW/cm². Preliminary calculations indicated that 1% duty factor is viable. The mode of heat transfer chosen is turbulent forced convection, the Dittus-Boelter heat transfer correlation was used. The heat removal is provided by pumping pressurized water through strategically placed coolant channels. Pressure drops through the channels were addressed, to ensure that boiling does not occur, and to comply with facility capabilities. The flow rates were limited by erosion considerations. Flow velocity limits for copper were within the recommended guidelines.[11]

The power density was supplied by the SUPERFISH code for the cavity configurations evaluated. The power density in the longer half cell is decreased by nearly 15%. Various 2-D axisymmetric models of the gun were generated to determine flow rates, and the positions and sizes of the coolant channels. Steady state thermal analysis was performed for the various evaluations. A transient analysis with 2 μ sec pulses and 5 kHz was performed and compared with a steady state analysis, the bulk and through the thickness temperature distributions were in good agreement, and only a 15°C peak surface temperature variation was experienced.

The operating pressure and temperature distributions are input to the structural model and the pressure and thermally induced deformations and stresses are calculated. The resulting displacements are evaluated to determine the variation in cavity deformations impacting the frequency and tuning of the cavity. The stresses are evaluated and compared to the various stress

categories in the ASME Boiler and Pressure Vessel Code. The combination of the stresses used for comparing the ASME allowables are conservative, since they include the thermally induced membrane stress in the Primary+Bending stress category, and the peak thermal stresses in the Primary+Secondary stress category.

The temperature distribution and a Von Mises Stress Intensity contour plot of the most recent analyses are shown in Figures 7 and 8, respectively, for a 2-D model of the first two cells of the gun. The peak temperature reported is 130°C, with a corresponding frequency shift of 4.4 MHz. The maximum stress intensity is less than 18 ksi (124 MPa) with an allowable of 31 ksi (214 MPa).

The effect of the waveguides and electric field pickup probes will be evaluated using a 3-D model. The cavity inner diameters will be sized so that thermal growth will tune the cavities for the operating frequency. Hot water will raise the temperature to proper levels to tune the cavities for low power operation. Water circulation flow rates will be controlled to selectively detune cavities so as to introduce field tilts between adjacent cells.

Number of cells	3 ^{1/2}
Laser radius ($1\sigma_r$)	4 (mm)
Pulse length ($\pm 2\sigma_t$)	8 (psec)
Cathode electric field (nominal)	100 (MV/m)
Beam momentum	10 (MeV/c)
Peak power	12.5 (MW)
Duty factor	1%
RF frequency	2.856 (GHz)

Table 1. Operational parameters of Gun II.

Charge	0.1 (nC)	0.5	1.0	3.0
Transverse emittance	1.9 (π mm-mrad)	2.3	3.4	8.9
Divergence	6.9 (mrad)	7.9	8.3	9.5
Momentum spread	0.7 %	1.1%	1.5%	2.3%
Exit radius (σ_r)	4.2 (mm)	4.6	4.9	5.4
Launch Phase	49°	55°	59°	63°
Current:				
Uncompressed bunch	25 (A)	118	220	571
Compressed bunch	428 (A)	2705	4224	7429
Brightness:				
Uncompressed bunch	6.9 (10^{12} A/m ²)	22.3	19.0	7.2
Compressed bunch	119 (10^{12} A/m ²)	511	365	93.7
UV-FEL user facility gain length:				
Uncompressed bunch	2.62 (m)	1.20	1.03	1.00
Compressed bunch	0.54 (m)	0.23	0.21	0.25

Table 2. Modeling results for Gun II for electron bunches of 0.1, 0.5, 1.0, and 3.0 nC.

FIGURE CAPTIONS

- Figure 1. Schematic of the present BNL $1\frac{1}{2}$ cell gun (Gun I).
- Figure 2. Vector plot from MAGIC of the electric field in the $3\frac{1}{2}$ cell gun (Gun II).
- Figure 3. Wakefield contours of the electric field (Log of the magnitude) of the bunch at various times a) 130° b) 145° c) 160° d) 175° .
- Figure 4. Variation of parameters through the $3\frac{1}{2}$ cell gun for a 1 nC bunch. a) Emittance and divergence, b) momentum (P) and momentum spread (dP/P).
- Figure 5. Longitudinal phase space at the exit of Gun II and the longitudinal phase space after ideally compressing the bunch (1 nC).
- Figure 6. Transverse phase space at the exit of Gun II (1 nC).
- Figure 7. Steady-state temperature distribution of the first cell and half of the following full cell for Gun II operating at an accelerating gradient of 100 MV/m, 1% duty factor.
- Figure 8. Von Mises Stress Intensity contours that result from the temperature distribution shown in Fig. 7.

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MAGIC VERSION OCTOBER 1990 DATE 8/21/91
 SIMULATION GUN5431-BEAM dI= 0.88cm, rad1= 4.112, 95 degree

VECTOR PLOT OF (E1,E2)
 AT TIME 8.75E-11 SEC
 VMAX = 1.02E+08

Uncompressed current: 220 amps
Compressed current: 4224 amps
Compression factor: 19.2

130. DEG C

126.

121.

117.

112.

108.

104.

99.3

94.9

90.5

86.1

81.7

77.3

73.0

68.6

64.2

17735. PSI

16557.

15379.

14201.

13022.

11844.

10666.

9487.

8309.

7131.

5953.

4774.

3596.

2418.

1239.

61.1

END

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