SIMULATIONS FOR THE HIGH GRADIENT, LOW EMITTANCE SUPERGUN RF PHOTOINJECTOR

A. Cahill, A. Fukasawa, J. Rosenzweig, UCLA, Los Angeles
B. Spataro, INFN, Frascati
A. Valloni, CERN, Geneva, Switzerland
L. Failace, RadiaBeam Technologies, Los Angeles

Abstract

A new S-Band photoinjector is being developed at UCLA that will feature a large accelerating gradient at 160 MeV/m creating a beam with approximately 6.5 MeV at the exit. Because of the large accelerating gradient and other considerations, such as cooling and manufacturing, the new Supergun will be coupled into using a coaxial method, rather than side coupling. With the large accelerating gradient we hope to create very low emittance beams on the order of 0.025 mm mrad. These beams can then be used for a number of purposes, mainly for high quality beams used in FELs. Electric simulations have been done using HFSS and Superfish. Heating and mechanical simulations were done using Ansys. Finally, beam simulations were completed with GPT.

INTRODUCTION

One of the large problems in creating suitable electron beams for X-Ray FELs such as LCLS is creating a low emittance beam inside the undulator. If the emittance of the electron beam is larger than the emittance of the photons [1], where the emittance of a photon is $\epsilon = \frac{\lambda}{4\pi}$, then the actual 3D gain length will be larger than the calculated 1D gain length. Due to Louisville's theorem [2] the normalized emittance of an electron beam can only increase along the beamline under energy conserving processes. To solve this the emittance directly following the photoinjector should be minimized. For a 1nm output the emittance is already 0.079 mm mrad, therefore we would require that the electron beam be <0.1 mm mrad. To accomplish this a S-Band BNL/SLAC/UCLA style1.5 cell RF photoinjector was chosen. S-Band was chosen, as opposed to a 11.424 GHz system, due to availability of klystrons. The other consideration is that the breakdown of approximately 240 MV/m in an X-band system compared to 160 MV/m in S-Band is not a large enough increase, particularly when considering the X-band system would likely have a starting phase further from peak voltage, to warrant the increase in complexity for machining and energy supply [3]. A coaxial coupling method was chosen for a few reasons: the focusing solenoid can be placed further upstream to maximize emittance compensation effects, the symmetric nature of the coupling minimizes multipole fields, and the cooling of the gun is more effective since there is no port attached to the full cell [4]. In the following we show a design for a photoinjector useful in low charge and low emittance settings.

RF DESIGN

The RF design was initially done with the 2D code Poisson Superfish [5], then it was finished in the 3D code HFSS from Ansys. The initial cell was chosen to be 0.4 times the distance light travels in half a period of 2.856 GHz. After this the full cell length was chosen so that the electrons would leave the cell as the RF reaches a zero crossing. This can be done using a particle tracking code, in this case GPT [6], where the length is varied until there is no deceleration on the electron beam at the end of the photoinjector. This photoinjector design is able to bring the electron beam to 6.4 MeV. An Elliptical shape was used to decrease the field increase on irises. The outer radii of the cells are chosen so that each cell resonates at the correct frequency. These are then modified slightly so that the fields are balanced between the cells and the entire cavity rings at the correct frequency, in this the fields are even to within 98%. The iris radius was chosen to be small to increase the shunt impedance, and since the gun will not run in a pulsed beam setting, wake fields will not be important to dynamics. The input is designed after the doorknob coupler used in a variety of coaxial designs, namely the Flash gun at DESY [7]. There are two ports on this design, one is an open waveguide and the other is a tunable short. The choice of using one open port rather than two was to avoid the complexity of building a waveguide system to split the incoming RF power that could also add asymmetries into the system. All of the geometry was chosen initially to critically couple the power in, $\beta = 1$ where β is the coupling constant. The β of teh cavity can be calculated by finding the VSWR of the system. If the caivy is under coupled then $VSWR = \frac{1}{\beta}$, and $VSWR = \beta$ when the cavity is overcoupled [8]. It is easy to tell if the cavity is under or over coupled by calculating the Smith chart of the system. This choice of coupling will be examined in the next section.

COUPLING CONSIDERATIONS

From the superfish calculations we can get the quality factor Q, and the shunt impedance per unit lenght Z. Choosing the klystron pulse to be 25MW and to have 1μs of fill time then the final voltage at that microsecond can be calculated [9].

$$E0 = \sqrt{\frac{4\beta Z P_{in}}{L(1+\beta)^2}}\left(1 - e^{\frac{-t\omega_0(1+\beta)}{2Q}}\right)$$

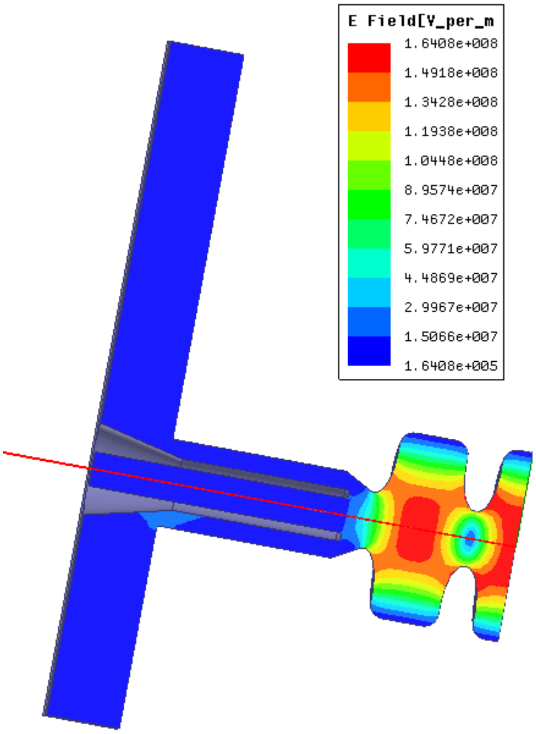

Figure 1: RF design of Supergun in HFSS.

Where P_{in} is the input power, L is the total length of the cavity, ω_0 is the angular frequency of the system, and β is the coupling constant. With this equation we can find the coupling constant that maximizes the gradient at the end of the fill time. In this situation the maximum occurs when $\beta = 2.1$. To get the required coupling constant, the inner conductor of the coax section can be moved further from the cavity, which increases the β. Once the photoinjector is manufactured then the short opposite the input waveguide can be moved to tune the coupling constant to the correct value. Once the nominal coupling constant is achieved, then the cavity will have 160MV/m on the cathode with a $1\mu s$ fill time and 25 MW input power.

THERMAL SIMULATIONS

To simulate the pulse heating of the photoinjector we used the multiphysics software package from Ansys. The model was first made in solidworks where a shell of copper was placed around the vacuum envelope from the HFSS simulation. Then water channels were added mostly in the irises and on the cathode, note that these channels are an approximation and not necessarily the final cooling design. The figure shows a quarter cross section to see the water channels Using Ansys it is possible to apply the resistive heating on the surface of the material while also doing a fluid dynamics simulation that shows that the water does not significantly heat up in the water channels. Using this technique we were able to show that there was no significant heating above 35°C even at 100 Hz rep rate and $1\mu s$ pulse length, which is a higher frequency than necessary for our

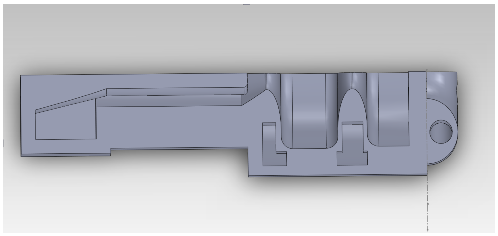

Figure 2: CAD drawing of water channels.

applications. The map of the pulse heating can be seen in figure 3.

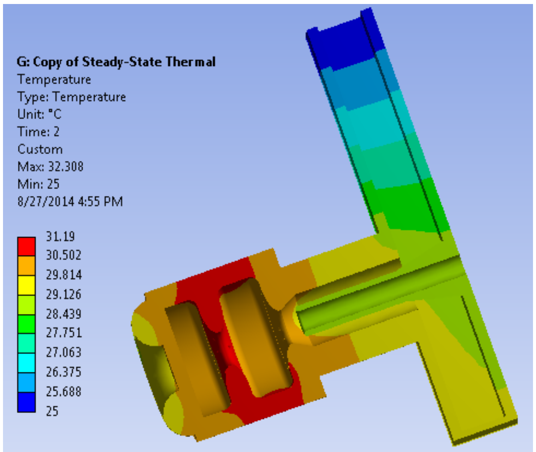

Figure 3: ANSYS simulation of Pulse Heating.

BEAM DYNAMICS

Since we are aiming for a low emittance beam, this is more easily achieved using a low charge beaml. Therefore, a 1 pC beam was chosen, which will be enough for the future planned uses of the electron gun. First, the electric field map from superfish was imported. The solenoid system was designed, one bucking coil upstream of the cathode to cancel the field on the cathode, and two other solenoids coils around the resonant cavity. There was also a standard SLAC 1.5 m linac inserted 1 m downstream to bring the particles up to 27 MeV. Next, the strength of the magnetic field was scaled to so that the transverse emittance was minimized after leaving the solenoid field. Finally, the pulse length and the electron beam radius on the cathode are optimized to also minimize the emittance. At this point the emittance has been reduced to 0.013 mm mrad for a 4 ps length and 20 μm full radius beam. This beam may be difficult to realize so the other possibility is to use a 4 ps and 50 μm full radius beam which would be realizable and still has a 0.025 mm mrad emittance. In the figures the large excursions are caused by the solenoid for the first large one, and the linac for the multiple bunch of excursions. These are not important since the emittance goes back to it's minimum value afterwards.

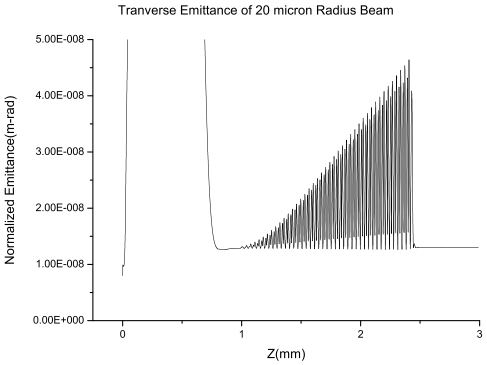

Figure 4: Emittance along beamline for $20\mu m$ full radius.

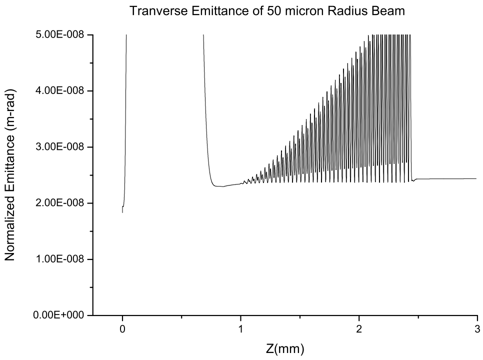

Figure 5: Emittance along beamline for $50\mu m$ full radius.

CONCLUSION

The electron gun described here has a low enough emittance to be usable in FEL applications. In the future we will have the gun manufactured and tested at UCLA and eventually used in tabletop undulator settings.

REFERENCES

[1] P. Schmueser et al. *Free-Electron Lasers in the Ultraviolet and X-Ray Regime* ISBN: 978-3-319-04080-6 Springer, New York, 2nd Edition, (2014)

[2] J. Rosenzweig *Fundamentals of Beam Physics* ISBN: 978-0-198-52554-7 Oxford, New York (2003)

[3] J. Rosenzweig, B. Spataro personal conversation, November, 2013

[4] J.-H. Han "Design and Optimization of an S-Band Photoinjector" In Proceedings of LINAC Victoria, British Columbia, Canada 2008

[5] LAACG, C. Allen, F. Krawczyk *Poisson Superfish* laacg.lanl.gov/laacg

[6] S.B. van der Geer, M.J. de Loos *General Particle Tracer* www.pulsaar.nl

[7] H. Schlarb et al. "Precision RF Gun Phase Monitor System for FLASH" in Proceedings of EPAC Edinburgh, Scotland 2006

[8] David M. Pozar *Microwave Engineering*. ISBN : 978-0-470-63155-3 Wiley, New Jersey, 3rd Edition, (2004)

[9] Thomas P. Wangler *RF Linear Accelerators* ISBN: 978-3-527-40680-7 Wiley, New Jersey, 2nd Edition (2011)