RF RESULTS AND BEAM DYNAMICS SIMULATIONS OF A PROTOTYPE S-BAND PHOTOCATHODE GUN

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Abstract

We are building a BNL/SLAC/UCLA type S-band photocathode gun as a photoinjector to a 30 MeV electron linac for FEL applications. We present results of RF simulations using SUPERFISH and GDFIDL, which agree reasonably well with cold-test results. We also report results of some beam dynamics simulations using PARMELA.

1 INTRODUCTION

The Beam Physics & FEL Laboratory, at the Centre for Advanced Technology (CAT), is building a 30 MeV photocathode linac as an injector for free-electron laser applications. The photoinjector to this linac will be the BNL/SLAC/UCLA Gun 3 model [1], giving a beam of around 3-4 MeV energy. For the linac structures we have chosen to build the Plane Wave Transformer (PWT) linac[2], first built by Swenson and further developed at UCLA, details of which are given elsewhere.

The gun is an S-band (2856 MHz) accelerating structure, with a copper photocathode. The drive laser system consists of a high-stability Nd:VAN laser oscillator, GE-100 from Time-Bandwidth, along with the CLX-1000 timing stabilizer, giving 7 ps pulses at a repetition rate of 102 MHz, with a timing jitter of better than 3 ps, and an amplitude jitter of around 1% rms. The laser amplifier, delivering 5 mJ in the IR, is presently being built at CAT. The gun will be powered by a 15 MW microwave system, which will be synchronized with the laser system.

We have built the first prototype of the photocathode gun, with which we have addressed various simulation and fabrication issues. Results of various RF simulations are presented in this paper, along with results of cold-cavity tests on the prototype cells. We have also built brazing prototypes of the gun out of ETP copper, before going on to build the final photocathode gun. In the next Section, we discuss results of the SUPERFISH and GDFIDL simulations of the structure, followed by a discussion of cold-test results in Section 3, and beam dynamics simulations in Section 4. We conclude with a discussion of our plans for the future in Section 5.

2 RF SIMULATIONS

Extensive RF simulations of the gun were performed using the two-dimensional code SUPERFISH, followed by a repetition of the same using the three-dimensional code GDFIDL, for two main reasons: (i) to get an idea of the agreement between results predicted by the two codes, and with results obtained from cold-tests, and (ii) to obtain a tolerance map for the structure, which is the sensitivity of its resonant frequency and other electrical properties to perturbations in its physical dimensions, based on which the mechanical engineering designing of the structure was done.

Since the RF gun structure is cylindrically symmetric, excluding the various ports, SUPERFISH simulations give a reasonably good idea of the electrical properties of the structure. Table 1 summarises some of the electrical properties of the half-cell, the full-cell, and the coupled half and full cells as calculated by SUPERFISH and GDFIDL.

Table 1. Summary of simulated RF parameters.

RF Parameter	SUPERFISH	GDFIDL
Resonant frequency	2855 MHz	2860 MHz
Quality factor	15,747	12,932
Effective shunt impedance	29 MΩ/m	28 MΩ/m
Characteristic Impedance	161 Ω	189 Ω

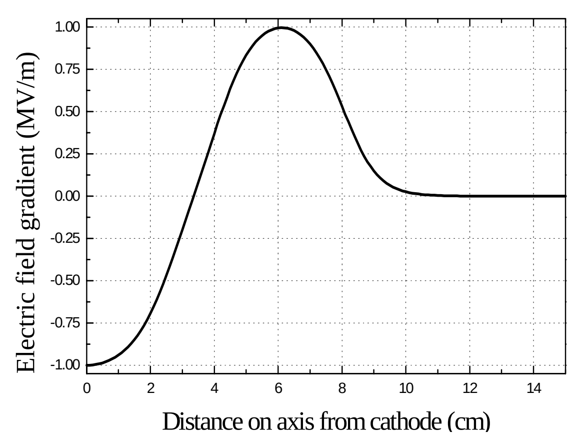

Figure 1. E_z field profile along axis of the gun.

Fig. 1 shows that the operating mode of the structure at 2856 MHz, as obtained from SUPERFISH simulations, is a π mode.

The resonant frequency of the gun was observed to be most sensitively dependent on the full cell diameter (~45 MHz/mm). The full cell diameter is also important in tuning the frequency of the π mode to the desired operating frequency of 2856 MHz. Lengths of the half and full cells also affect the resonant frequency by about 10 MHz/mm and 12.5 MHz/mm respectively. A change in the length of the cells is like a change in the value of capacitance of the equivalent circuit resulting in a change in the resonant frequency. A similar effect is also observed by changing the size of the aperture coupling the two cells. Although the effect on resonant frequency is not very strong (~ 200 kHz/mm), it affects the coupling coefficient between the two cells, thereby affecting the frequency of the π mode and the bandwidth of the structure (~ 4 MHz). These simulations for the tolerance map were first performed using SUPERFISH, and subsequently confirmed using GDFIDL for the same axi-symmetric structures. Based on these simulations, the mechanical engineering design of the structure was finalized with geometric and dimensional tolerances of 10 – 30 μm for it's various dimensions, which translates to a frequency tolerance of a few hundred kHz [3].

Prototypes of the half and full cells were fabricated as per the mechanical design, and inspected on a Coordinate Measurement Machine (Carl Zeiss). A pair of brazing prototypes with all ports was also made to determine the optimum number of brazing cycles required for brazing the gun assembly. The filler alloy used for these trials was copper-silver eutectic (72-28) in wire and foil forms. With appropriate fixturing, it was found that all the joints on the gun body, excluding the cathode plate, could be brazed in one cycle. However, to tune the coupling coefficient β between the waveguide and the structure, it might be necessary to braze the waveguide and the vacuum ports in a separate cycle.

3 COLD TESTS

The simulations discussed earlier cannot be used to compare results for individual cells with those obtained from cold-tests. From mechanical engineering considerations, the half and full cells individually are dimensionally different from the cells simulated earlier. However, when assembled together, they give the designed gun structure. Hence, simulations using SUPERFISH and GDFIDL were repeated for the cells as per the mechanical engineering designs, resulting in resonant frequencies different from those in Table 1. These results are summarised in Table 2.

Cold test measurements were performed on the prototype half and full cells individually and when they were coupled, using a spectrum analyzer [Rhode & Schwarz, Mod. FSP7] at input power levels of about 1 mW. Slots for RF and vacuum ports were used to inductively couple microwave power from a signal generator [Rhode & Schwarz, Mod. SMT03], both, into and out from the gun structure. A bead-pull set-up with a teflon bead was designed and developed for the r/Q measurements.

Table 2. Summary of cold-test results.

	SUPERFISH (MHz)	**Cold tests** (MHz)
Full cell	2789	2795
Half cell	2854	2898
Coupled cells	2855	2875
r/Q –coupled cells (Ω)	171	192

The measured full cell resonant frequency compares reasonably well with the simulated value. Since the simulated values correspond to SUPERFISH results, which do not include contributions from the ports, GDFIDL simulations were preformed to determine the effect of port openings. A frequency change of about 4 MHz was obtained in the presence of ports, which improves the agreement between the simulated and measured values of resonant frequency for the full cell. For the half cell, inspection on a CMM showed that a programming error of the CNC machine had reduced the length of the half cell by 6 mm compared to the design value. From the frequency tolerance map, this corresponds to a frequency change of about 60 MHz, resulting in a modified resonant frequency of 2914 MHz. While calculating the resonant frequency of the fabricated half cell, the cathode plate was considered to form one end wall, along with a helicoflex seal. During the cold tests, since the seal plates were not yet brazed, no helicoflex seal was used. Consequently, the length of the cold-tested half cell is shorter than that of the simulated half cell resulting in a higher resonant frequency. The change in length of the half cell also affects the resonant frequency of the coupled cells, as is evident from Table 2. The agreement between the simulated and measured values of resonant frequencies is, however, better than 0.5%.

4 BEAM DYNAMICS

The beam dynamics of an intense, relativistic electron beam with a Gaussian distribution of particles in the longitudinal and transverse planes was studied using PARMELA. The simulations were performed with 10,000 super particles with 1 nC charge per pulse of 10 ps duration.

In the presence of small accelerating forces, it is observed that space charge forces dominate the beam dynamics, causing divergence of the beam. As the accelerating forces increase, electrons get accelerated to high energies over very short distances, causing a reduction in the divergence. However, since the accelerating force is itself time-dependent, and since the gun is operated in the longitudinally stable region of the

RF cycle, i.e. close to 30 degrees (where the crest of the RF wave corresponds to 90 degrees), the net effect of the space charge and RF forces causes a deterioration in the emittance of the electron beam. In order to study this effect in different regions of the RF gun, we have performed PARMELA simulations by treating the half and full cells separately, as shown in Fig. 2. It is observed that at the end of the full cell, the electrons experience an extra transverse defocusing force causing an increase in the beam emittance. This is observed to increase with increasing field gradients.

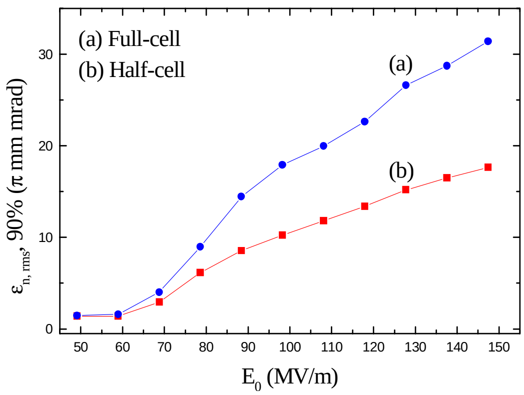

Figure 2. Transverse emittance variation with field gradient.

The dependence of the energy gain of the electrons, and of their energy spread, on the injection phase is shown in Fig. 3. These simulations show that a minimum energy spread of about 0.2% can be obtained by injecting the beam at a phase of 30 degrees, which also corresponds to the maximum energy gain in the gun. For injection phases from 10 degrees to 70 degrees, the energy spread is observed to vary from a minimum of 0.2% to a maximum of about 13.5% of the average energy gain.

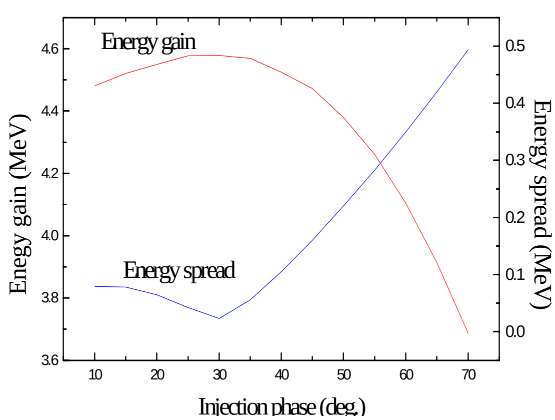

Figure 3. Energy gain and energy spread in the gun as a function of laser injection phase.

Studies were also performed to determine the variation of the transverse normalized emittance of the beam with the injection phase of the electrons. It is observed that for a minimum transverse emittance, the injection should be done at a phase of 30 degrees, which corresponds to the phase for maximum energy gain and minimum energy spread in the structure. Details of these simulations are reported elsewhere[4]

The length of the bunch is also observed to change depending upon the injection phase of the electrons. With an initial electron bunch length of 10 ps, which corresponds to the length of the laser pulse, the bunch length shrinks to 4 ps at the exit of the gun for an injection phase of 10 degrees, while for injection close to 60 degrees, the bunch length does not change much. This is as expected since best bunching occurs close to zero degrees, while close to the crest bunching is almost absent.

5 CONCLUSIONS

An RF photocathode gun has been studied using SUPERFISH and GDFIDL codes, based on which prototype half and full cells have been fabricated. Cold-tests performed on these show reasonably good agreement with results obtained from simulations. A study of the beam dynamics in the gun indicates that for an injection phase of 30 degrees, an energy gain of about 3 MeV is possible with a peak accelerating field gradient of the order of 65 MV/m. A normalized transverse emittance of about 3π mm.mrad. is obtained for the beam.

Further studies are currently underway to reduce the emittance by using the emittance compensation technique using a solenoid at the exit of the gun. Fabrication of the prototypes of the half and full cells have helped in performing a feasibility study for fabrication of the final structure, and efforts are currently underway to build the second prototype of the structure, which could also be used for hot-tests.

We acknowledge the help rendered by Mr. S. Jafar Ali in finalizing the AUTOCAD drawings for the structure.

6 REFERENCES

[1] B.E. Carlston, “New Photoelectric Injector Design for the Los Alamos National Laboratory XUV FEL Accelerator”, NIM A285, 313-319 (1989).

[2] K.K. Pant et al, “Fabrication and RF studies on a prototype PWT linac structure”, this conference, Arvind Kumar et al, PRST-AB, Vol.5, 033501 (2002).

[3] Arvind Kumar, K.K. Pant, and S. Krishnagopal, “Preliminary design study and cold-tests of a photocathode rf gun”, CAT Internal Report, CAT/2001-04(2001).

[4] Arvind Kumar, K.K. Pant, S. Krishnagopal, “Design & beam dynamics simulations of an S-band photocathode gun”, submitted to PRST-AB, 2002.