DESIGN OF THE HIGH REPETITION RATE PHOTOCATHODE GUN FOR THE CLARA PROJECT*

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Abstract

The CLARA (Compact Linear Accelerator for Research and Applications) injector is required to deliver ultrashort single electron pulses with a charge of 250 pC at a repetition rate of 100 and/or 400 Hz. It should also provide 2 µs trains of twenty 25 pC pulses at a repetition rate of 100 Hz. To meet this challenge, a 1.5 cell S-band photocathode gun with a field of up to 120 MV/m and coaxial coupling has been chosen. The relative length of the first cell of 0.5 is decided on the basis of beam dynamic simulation with the goal to obtain optimal beam for CLARA parameters. In order to improve the amplitude and phase stability of the RF field, the gun is equipped with an RF probe which will provide feedback. The gun and coupler were designed to accept up to 10 MW peak and 10 kW average RF powers. Cooling will be achieved by 9 water channels cut into the bulk of the copper cavity. The coupler will be transitioned from waveguide to coax using an innovative H-shaped dual feed system.

INTRODUCTION

A 1.5 cell, 2998.5 MHz (S-band) photocathode RF gun with a coaxial coupler, shown in Fig. 1, has been designed at STFC Daresbury Laboratory in collaboration with Institute for Nuclear Research, Moscow, to deliver high brightness electron beams for the CLARA FEL test facility [1]. The main specification of the gun is summarised in [2] and the conceptual design described in [3]. In this paper we will give more detail of the gun cavity RF design and its thermal regime and practical cooling system solution.

RF CAVITY DESIGN

Cavity Shape Optimisation

The cavity shape was optimised using the Superfish [4] code. The first cell length was defined using ASTRA [5] beam dynamics simulations [3]. Cavity shape parameters were varied using a Mathematica [6] front-end, which was used to optimise both the frequency and field flatness of the cavity by varying the cell radii for each value of the changing parameter. It was found that the transverse emittance requirements were met for wide range of the first cell length, and a final value of 0.5 of the half-wavelength was therefore chosen where longitudinal beam properties are optimal [3].

The next step was optimisation of the cell to cell coupling iris. It was found that an iris ellipticity of 1.75 at an iris thickness of 16 mm was sufficient to reduce the maximum surface electric field on the iris to the same level as the surface field elsewhere in the cavity, a value of 113 MV/m. This is just 94% of the cathode field, and an acceptable value.

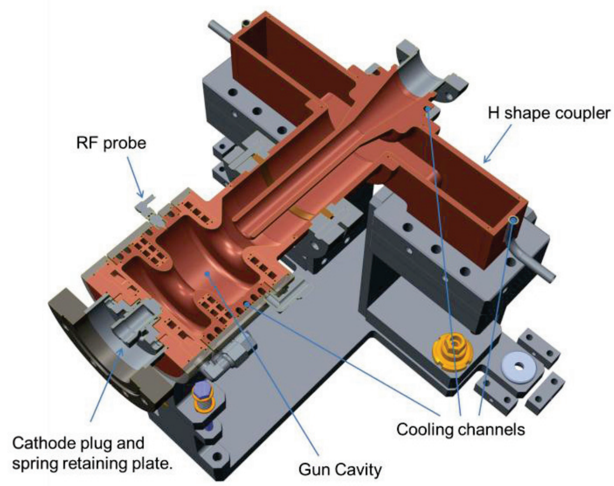

Figure 1: Overview of the gun cavity design.

The geometric shunt impedance R/Q of the cavity was then maximised whilst keeping the mode separation above a conservative value of 20 MHz. It was found that at an iris radius of 13.4 mm R/Q reaches its maximum value keeping the mode separation to 20 MHz.

The edges of the cells were rounded to maximise overall quality factor of the cavity. A study found that whilst increasing the radius of curvature of the rounding does decrease the integrated magnetic field on the surface, the effect is not large. The rounding radii on the first cell were chosen to be 3 mm, and those on the second cell 4 mm, dictated mainly by mechanical and thermal constraints.

RF Probe Considerations

The CLARA gun design requires provision for a RF probe allowing RF feedback to be used. The only realistic position of the probe in this gun is on the equator of the second cell, due to the need for cooling channels accommodation in the copper. In order to ensure that the probe could couple to the cavity electric field, it was offset from the centre of the cell. The position of the probe was

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ISBN 978-3-95450-142-7

chosen to be 3 mm from the centre of the cavity, towards the cathode, in order to minimise the disruption to the cooling channels.

The cavity equator is the location of strong wall currents. In order to minimise the localised heating caused by the RF probe, its aperture was rounded by 2 mm in diameter. This limits the localised temperature rise to a maximum of 14 K, compared to the 10 K rise in the same conditions at locations in the same azimuthal position but unaffected by the probe. This limits the risk of material damage on the copper.

In order to preserve symmetry, a dimple will be added on the opposite side of the cavity. A depth of 1 mm is sufficient to ensure that frequency and field flatness are unaffected.

MULTIPACTOR STUDY

The multipactor effect is a common problem in large bore coaxial lines [7], and increasing the coaxial radii to allow better laser access could increase the chance of multipactor development. The preliminary design coaxial line with an outer diameter of 50 mm was simulated in CST Particle studios tracking solver [8,9] and strong multipactor were found in the RF power band between 2-8 MW. This is very close to the operating power of the gun which could be problematic to reach. In order to move the multipactor band the coax radii could be made smaller to push the band down to a level that can be processed through or to increase the radii to push it up above the operating power. In order to keep the improved laser access the aperture was chosen to be 62 mm. Simulations show that the multipactor threshold was increased up to 18 MW.

However another multipacting trajectory was also found at the transition between the coaxial and rectangular waveguide sections at a power of 4-8 MW (Fig. 2). This is likely due to the increased field in this region. Further aperture increases were not possible without increasing the rectangular waveguide width so this may be an issue. The trajectories are likely to be affected by the magnetic field of the main gun solenoid [10]. To study the effect of the solenoid field on the multipactor at the transition a static magnetic field orientated parallel to the coaxial line was introduced to the simulation. A magnetic field of less than 100 mT had no effect on the multipacting bands and fields of more than 500 mT completely eliminated the multipacting. CLARA is likely to have around 250 mT at the transition. At this field a very narrow multipacting band still exists at 5 MW.

GUN COOLING

In order to provide effective cooling of the CLARA gun cavity it incorporates 9 cooling channels the locations of which are optimised for the heat load distribution and to maximise cooling of the RF probe region (Fig. 3). The cooling design of the cavity was performed using magnetic field distribution, responsible for the RF heating, calculated with Microwave Studio CST [8] in combination with ANSYS CFX code [11] for fluid calculations and ANSYS Workbench for estimation of displacements, frequency shift and stresses due to RF heating.

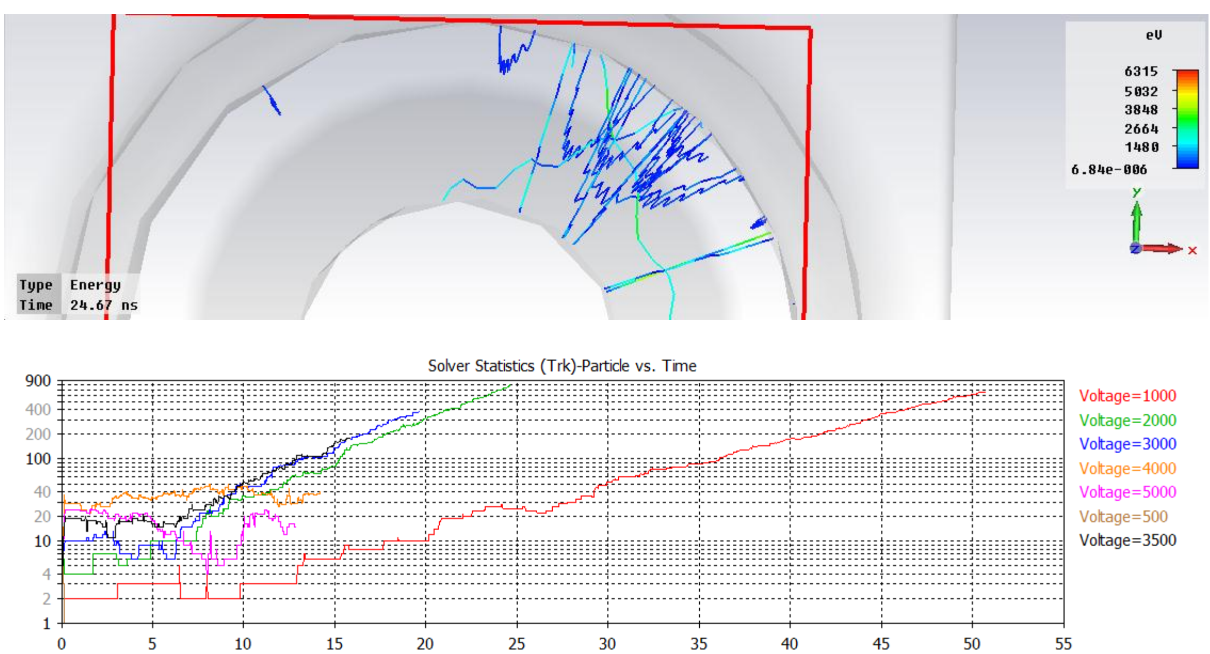

Figure 2: Multipacting trajectories in the coaxial coupler transition (top) and the number of electrons versus time at various voltages (bottom), RF power P is calculated as $P=2V^2$.

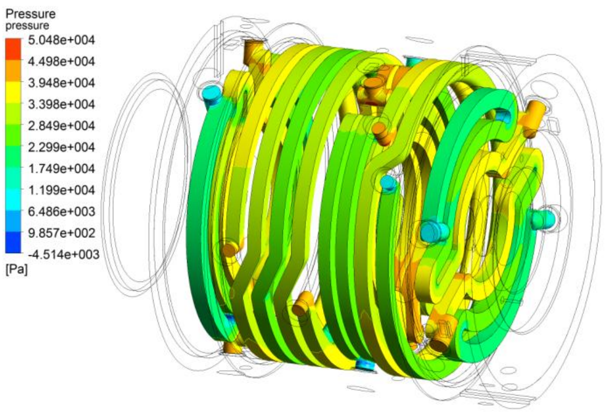

Figure 3: Pressure profile at the surface of the cooling channels.

Loads

The results of magnetic field distributions were scaled for the highest heat load operation mode which is 100 MV/m at 400 Hz. The field distributions were broken into several areas with peak heat flux for each region calculated. This flux was then averaged over time for operational repetition rate of 400 Hz and 3 µs pulse length. Average flux values for the various regions were then assigned to the corresponding surfaces within an ANSYS CFX model. The average total heat dissipated in the cavity is estimated as 6.8 kW.

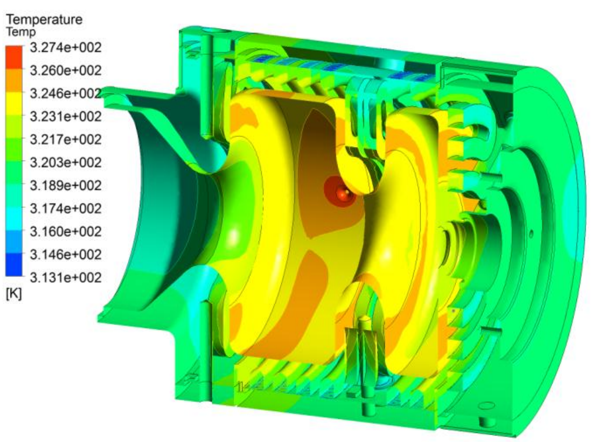

Figure 4: Temperature profile at the gun cavity surface.

Cooling Setup

Models for the water flow within the cooling channels were generated using ANSYS Design Modeller. The water was set at 40°C, with static inlet pressure of 0.4 bar and static outlet pressure of 0.1 bar for each channel. Fig. 3 shows the pressure profile at the surface of the cooling channels. The gun cavity was modelled as OFHC copper, outer jacket as 316L Stainless Steel. The wall roughness of the cooling channels was set to 16 µm. Air cooling with convection co-efficient 4 W/m^2/°K at reference temperature 23°C applied to all external surfaces.

Results of the Cooling Simulation

Magnetic field is highest on the perturbation of the RF probe. In this region the highest temperature rise of 14°C is observed against 10°C on the over points of the cavity equator. Overall temperature distribution is shown in Fig. 4.

From room temperature (23°C) to full operating temperature with RF the cavity cell radii increase by 18 µm (Fig. 5). Using a reference temperature of 40°C i.e. that of the cooling water gives a change in cell radii of 5.6 µm, which is the deformation caused by the introduction of the RF power. Using the inbuilt high frequency solver in ANSYS Multiphysics it gives a predicted frequency shift of -0.427 MHz. This is in agreement with the predictions made using the Microwave Studio CST code. Maximum stress in the cavity is 29 MPa at the probe penetration, which is at the acceptable limit for annealed copper. Highest stress in the rest of the body is 14 MPa.

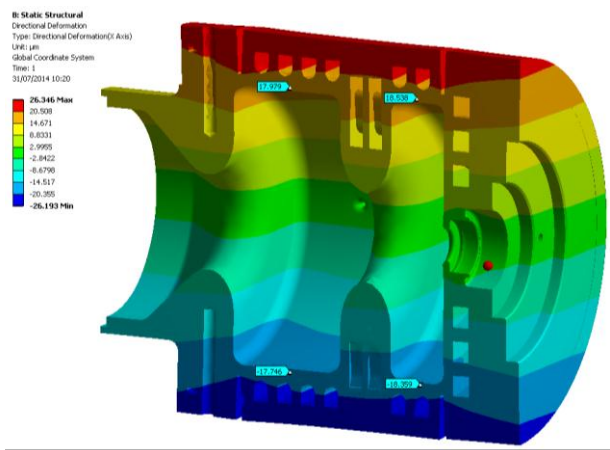

Figure 5. Radial cell deformation from room temperature to full operating temperature with RF.

CONCLUSION

Optimisation of the cavity shape allows for design of the RF gun which is able to operate at an accelerating field of up to 120 MV/m on the cathode and at a repetition rate of up to 400 Hz. Proper selection of the separation iris size and shape allows for limiting surface electric field on the cavity to 94% of the photocathode field keeping the quality factor at a level of 14000 and the mode separation more than 20 MHz. Simulation of multipactor in the coaxial coupler has shown that at a reasonable outer coupler diameter of 62 mm the risk of multipactor development is significantly reduced at a RF power of higher than 8 MW. Simulations of the cavity cooling system have shown that an average power of 6.8 kW will be dissipated for 100Mv/m 400Hz operation mode, with a maximum steady state temperature rise of 14°C on the RF probe penetration.

 ISBN 978-3-95450-142-7

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