NUMERICAL STUDY OF THE RF HEATING OF AN L-BAND GUN

Jang-Hui Han*, Houcheng Huang, Diamond Light Source, Oxfordshire, United Kingdom

Abstract

As an injector for the New Light Source facility for the UK, an L-band copper photocathode gun is designed. Because the gun will be operated with about 4.5 MW RF peak power, 16 μs pulse length and 1 kHz repetition rate, the average power will reach about 70 kW. To precisely stabilise the electron beam parameters at the gun, the RF field distribution during RF operation must be controlled. The RF field induces localised heating on the cavity surface. This non-uniform temperature distribution deforms the cavity and affects the RF field distribution and therefore the electron beam dynamics. Here, we model a copper RF gun cavity and numerically calculate the temperature distribution and the stress over the cavity surface. Then, the RF field distribution change caused by the cavity deformation is estimated.

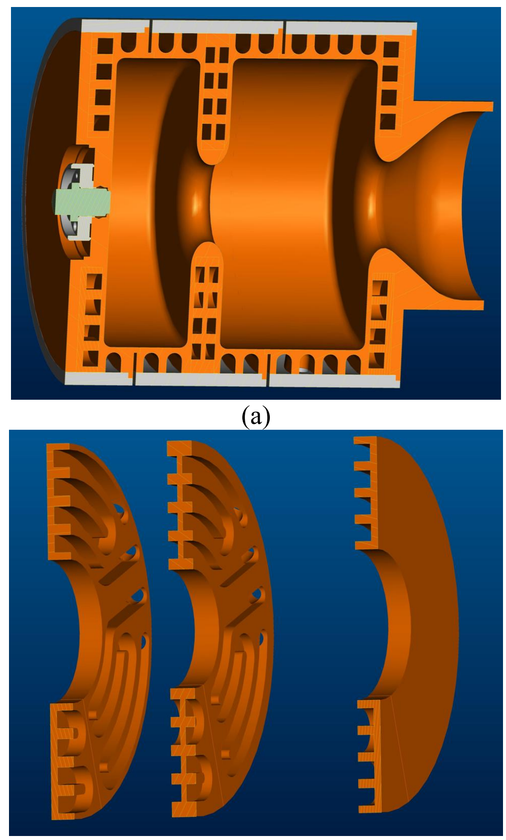
INTRODUCTION

The UK's New Light Source (NLS) facility is proposed to have 1 kHz repetition and 1 keV FEL photon energy as a baseline specification [1]. To satisfy such requirements an L-band copper gun cavity was designed [2]. This gun is based on the DESY PITZ gun4 which has been developed for European XFEL and successfully tested at PITZ [3]. Compared to the PITZ gun, this gun has an optimised cavity cell length and improved cooling water channel [2] (see Fig. 1). The main cavity body will be made from Oxygen-free high conductivity (OFHC) copper. The photocathode plug and the outer jacket of the cooling channel will be made from molybdenum and stainless steel, respectively. The gun cavity will operate with about 4.5 MW RF peak power, 16 μs pulse length and 1 kHz repetition rate.

When RF power is fed into the cavity, the temperature distribution is not uniform (see Fig. 2). The non-uniform temperature distribution over the cavity induces a non-uniform cavity deformation. This deformation would affect the RF field distribution and may deteriorate the electron beam quality. In this study, the RF field distribution of the cavity is calculated with SUPERFISH [4]. Then, the cavity deformation is analysed with ANSYS [5] and the RF field distortion by the deformation is estimated.

RF GUN DESIGN

In an RF gun, an electron beam is generated with a laser pulse and accelerated to a relativistic speed to minimise beam quality degradation due to the space charge force. In this design, the gun must operate with 4.5 MW to produce 50 MV/m accelerating field at cathode. Such a high RF power increases the surface temperature of the cavity. Because the current induced by the RF field is not uniform over the cavity, the temperature rise is not uniform also. In this gun design, the water-cooling channel is distributed over the cavity so that the cavity temperature rise and the non-uniformity are minimised. Figure 1 shows the cavity geometry and the cooling water channels. The four cooling channels in an iris are arranged to have two mirror symmetries. In Fig. 1(b), one full channel and part of two other channels are shown.



(a)

(b)

Figure 1: Gun cavity geometry and cooling-water channels. A cut of cavity geometry (a) and cooling water channels in the back plane and irises (b). Dark red colour presents the material is OFHC copper, pale green molybdenum and bright grey stainless steel.

The field balance between the first and second cells was configured to be 1.04:1 when the cavity is not heated. In this case, the heat loss density at both cells is about equal according to SUPERFISH simulation. If the field balance changes for different RF power, the electron beam dynamics would be also affected.

RF HEATING

The RF field distribution and the heat loss to the cavity surface were calculated with SUPERFISH. For the calculation, the cavity temperature was set to 50°C as a

*jang-hui.han@diamond.ac.uk

first assumption. When the cavity temperature increases, the quality factor of RF cavities decreases and more RF power is required for 50 MV/m at cathode (Table 1). As discussed later, the average temperature of the cavity surface will be higher than 50°C. The calculation procedure discussed here should be iterated with newly found working temperature. Here, we show only the first step.

Table 1: The cavity temperature, the quality factor and the RF power required for 50 MV/m at cathode

Temp	20°C	30°C	40°C	50°C	60°C	70°C
Q	22949	22510	22097	21705	21333	20980
Power (MW)	4.119	4.200	4.278	4.356	4.431	4.506

With the heat loss information from the SUPERFISH calculation, the temperature distribution over the cavity was calculated with ANSYS (Fig. 2). To apply different heat loss density to different wall locations, the wall surface was divided to 5 mm thick bands with cylindrical symmetry for both SUPERFISH and ANSYS simulations. For ANSYS simulation, global average mesh size was set to 2.5 mm. A water temperature of 30°C and a water speed of 2.5 m/s through the water channel were used. Air cooling at 22°C was applied for the outer surface of the cavity.

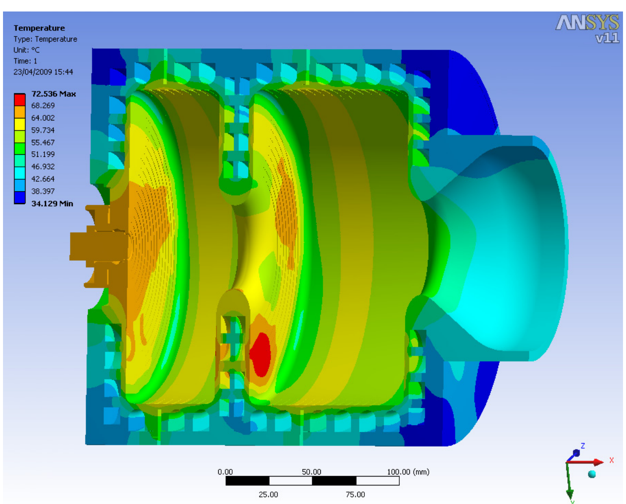


Figure 2: Temperature distribution over the cavity for 70 kW RF average power.

For the conditions above, the temperature at the hottest area is calculated to be 72°C, where two cooling channels in the iris meet (see Fig. 1 for the cooling channel arrangement). Due to lack of cooling water channel, the cathode area is also hot even though the RF heat loss is very small in the area. In reality, the cathode area and the coupler tube may be cooler than this simulation because those areas will be connected with other vacuum tubes and will have additional convection.

CAVITY DEFORMATION

Cavity stress and deformation induced by the non-uniform cavity temperature were calculated with ANSYS also. The calculated stress is shown in Fig. 3. The maximum stress point is the cathode plug and the cathode slot of the cavity. The plug is made from Molybdenum and the cavity is made from OFHC copper. In the ANSYS calculation, the thermal expansion coefficients of 1.7×10^{-5} °C^{-1} and 5.3×10^{-6} were used for OFHC copper and Molybdenum, respectively.

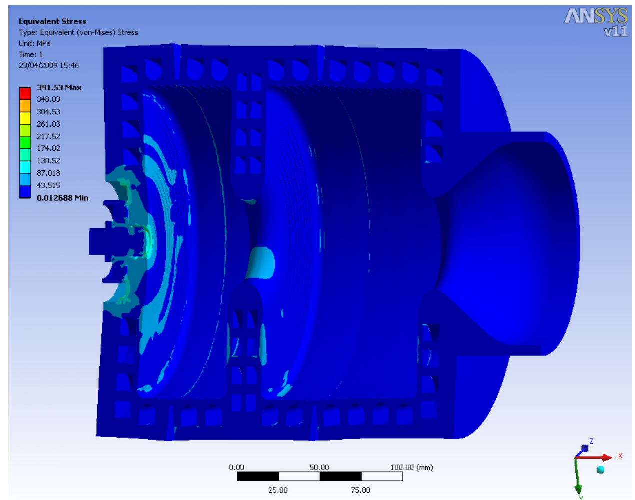


Figure 3: Stress distribution for the temperature distribution in Fig. 2. The deformation is magnified for visualisation.

For the deformation calculation, the cathode plug holder (made from Stainless Steel) was used as the reference point. With the cavity heated, the back plane becomes convex (see Fig. 4). When 70 kW RF average power is applied, the cathode surface is shifted forward by 16 µm, the back plane area around the cathode forward 24 µm, the back plane area near the outer edge backward by 14 µm. The centre of the iris between two cells is

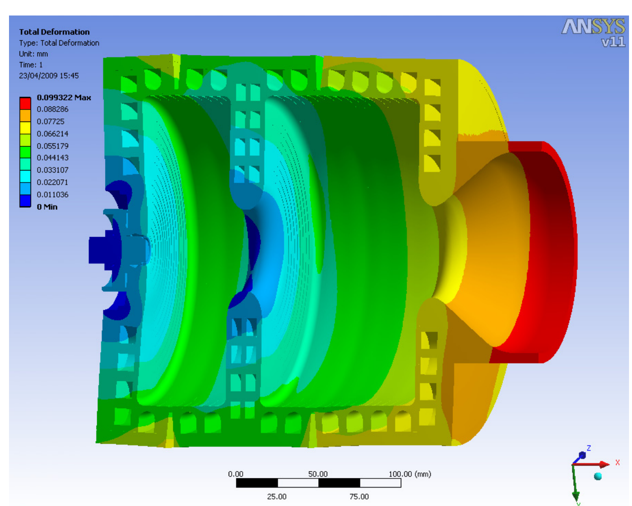


Figure 4: Cavity deformation by the stress distribution in Fig. 3. The deformation is magnified for visualisation.

shifted forward by 11 μm and the centre of the second iris is forward by 71 μm. The radius of both the cells expands by 40 μm. Compared to the non-deformed case, the resonant frequency decreases by 0.675 MHz.

To keep the resonant condition of the cavity, the cooling system should be controlled so that the cavity is in resonance both cases with and without the RF power in the cavity. The effect of the cavity deformation may be compared with the case that the cooling water temperature is set to 45°C and no RF power fed in. The cathode surface is shifted forward by 11 μm, the back plane area around the cathode forward 21 μm, and the back plane area near the outer edge backward by 9 μm. The centre of the iris between two cells is shifted forward by 21 μm and the centre of the second iris is forward by 80 μm. The radius of both the cells expands by 41 μm. Compared to the non-deformed case, the resonant frequency decreases by 0.664 MHz.

EFFECT ON RF FIELD DISTRIBUTION

When the cavity is deformed, the RF field distribution is also affected. Here, we compare three cases: (1) non-deformed cavity with uniform temperature distribution at 50°C, (2) no RF and 45°C water, and (3) 70 kW RF average power applied and 30°C cooling water applied. As mentioned earlier, the field balance was set to 1.04 for case (1). This was our starting point for the thermal calculations; when no cavity deformation is applied. For case (2), the back plane becomes convex because the outer area of the back plane is shifted backward with respect to the cathode area. The volume of both cells get larger, and the RF field balance changes to 1.01. For case (3), the cavity back plane gets convex more. The balance changes to 1.0.

CAVITY HEATING DURING RF PULSE

In addition to the cavity temperature rise caused by the RF average power, RF heating during the RF pulse produces extra temperature rise. Because the heat dissipation from the cavity inner surface to the body is not fast enough compared to the heating speed during the RF pulse, the temperature of the cavity inner surface rises during the RF pulse. After the pulse, the increased cavity surface temperature monotonically decreases until the next pulse comes into the cavity. This temperature rise may result in further cavity deformation and therefore beam dynamics change. Furthermore, this fast temperature rise may introduce fatigue in the cavity body. According to Ref. [6], the temperature rise during an RF pulse, T_s, has a relation: $T_s \sim P_d \cdot \sqrt{\tau}$, where P_d RF power in the RF pulse and $\sqrt{\tau}$ pulse length. Using this relation, the temperature rise for a 4.5 MW and 20 μs RF pulse is estimated to be 3.4°C at the hottest area on the iris, which would make negligible effect compared to the effect by the RF average heating. This temperature rise would not produce serious fatigue on the cavity material also.

SUMMARY AND OUTLOOK

For 70 kW RF average power, the cavity temperature will rise up to 72°C at the hottest area in the iris when the cooling water temperature is 30°C. With the present configuration, the cavity deformation may change the RF field balance between the cavity cells from 1.04 to 1.0. The preservation of the field balance during RF operation may be achieved by changing the initial field balance to about 1.02 and the back plane to be thicker, which should be confirmed with further numerical study. If the field balance is changed so, the heat loss density in the first cell will be relatively decreased compared to the second cell. For the next iteration of the study, the cavity temperature should be around 60°C for heat loss calculation.

A simple calculation with a formula was made for the estimation of the temperature rise during an RF pulse. The rise may be about 3.4°C, which does not seem serious. Numerical calculation with ANSYS is under preparation for the pulsed heating.

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