THERMAL SIMULATION OF AN ENERGY FEEDBACK NORMAL CONDUCTING RF CAVITY

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Abstract

Thermal simulation has been performed for an energy feedback normal conducting RF cavity. The cavity is going to be used as a fast actuator to regulate the arrival time of the electron bunches in fs level in FLASH. By measuring the arrival time jitter of one bunch in a bunch train, the designed cavity apply a correcting accelerating or decelerating voltage to the next bunches. The input power of the cavity is provided by a solid state amplifier and will be coupled to the cavity via a loop on the body. To achieve the fs level precision of the arrival time, the cavity should be able to provide accurate accelerating voltage with a precision of 300 eV. We performed thermal simulation to find out the temperature distribution of the cavity and make sure that heating will not affect its voltage precision. The simulation results show that by using two input loops the coupling constant will vary from 4.11 to 4.13 during the operation of the cavity which effect on the bunchs' arrival time would be less than 0.25 fs. While using just one input loop can lead to an error of about 1 fs.

INTRODUCTION

The Free Electron Laser FLASH at Hamburg provides soft X-ray sources to be used in studying the chemical and molecular reactions. For the FEL user it is of high importance to have a femtosecond level precision of synchronization between the FEL pulse and the external laser in pump prob experiment. Therefore it is necessary to keep the arrival time of the electron bunches stable in femtosecond level. At the moment, there is an arrival time jitter of ± 150 fs (peak-peak) which is being stabilized using beam-based feedback loops [1]. Further minimizing the bunch arrival time jitter requires faster actuators, e.g. a normal conducting cavity with higher bandwidth compared to narrow-band superconducting cavities. A normal conducting cavity is therefore designed for this purpose. This cavity is going to be installed at the FLASH main line before the magnetic bunch compressor as shown in Figure 1. The cavity has to be able to provide a maximum accelerating voltage of 50 kV with a half bandwidth of 500 kHz. Concerning the space limitation in FLASH a side coupling to this cavity is required. Since the input power of the cavity is about 1 kW it seems to be most efficient if the input power could be coupled to the cavity via a loop antenna instead of a waveguide coupler. In addition to space limits, it is more convenient to adjust the coupling constant by engaging the loop couplers. Besides, since the power supply is a solid state amplifier whit a coaxial cable as output it would be easier to connect its output directly to a feedthrough instead of using a coaxial-to-waveguide converter.

Since this cavity is designed to correct the arrival time of the bunches on the femtosecond level, it seems to be necessary to investigate the phenomena that can affect this precision. One of the phenomena that might affect the precision of the cavity operation is increasing the temperature of different parts specially the coupler during the operation. In this paper we study the thermal situation of the cavity. First the design of the coupler is described in the following section and the thermal simulation results has been discussed in the last section .

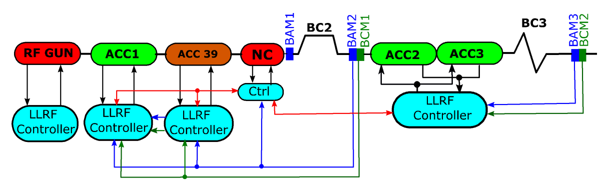

Figure 1: Place of installation the normal conducting cavity (NC) at FLASH. The low level RF (LLRF) controller systems are shown with blue boxes, ACC1, ACC2 and ACC3 are the accelerating components each of them are made from 8 TESLA cavity modules. BAM and BCM stand for bunch arrival time and bunch charge monitors, respectively. The magnetic bunch compressors (BC2 and BC3) are also shown.

INPUT COUPLER DESIGN

A four cell pillbox cavity has been designed. After designing the cells of the cavity, the most important part is to design its input coupler. As mentioned, it is required to have a half bandwidth of 500 kHz. Simulations show that for a normal conducting pillbox cavity made from copper and operating at 3 GHz frequency, the unloaded quality factor Q_0 is about 16000 while 500 kHz half bandwidth requires a loaded quality factor of 3000. Therefore the best way is to decrease the external quality factor. By changing the coupling constant between the cavity and its coupler one can change the external quality factor and subsequently the band with of the cavity. However, by changing the coupling constant the accelerating voltage also varies. For a cavity with the effective shunt impedance of r, input power of P_{in}, and the coupling constant of β the accelerating voltage can be written as [2]:

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$$V_{acc} = \sqrt{P_{in} r} \frac{2\beta^{1/2}}{1+\beta} \quad . \tag{1}$$

On the other hand the half bandwidth of a cavity can be written as a function of the resonant frequency, the quality factor, and the coupling constant:

$$f_{1/2} = \frac{f_0}{2Q_L} = (1+\beta)\frac{f_0}{2Q_0} \quad , \tag{2}$$

where f_0 is the resonant frequency, Q_L is the loaded quality factor and Q_0 is the unloaded quality factor of the cavity. For the designed cavity the unloaded quality factor is about 16000 and the effective shunt impedance is about 8 MΩ. If we consider the input power of the cavity to be 890 W peak which is equal to the output of the amplifier that is going to supply the input power of the cavity, the accelerating voltage and the bandwidth of the cavity are shown in Figure 2 as a function of the coupling constant.

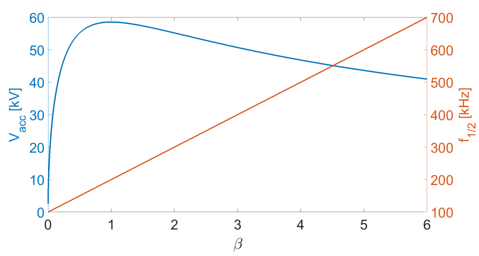

Figure 2: Influence of the coupling constant on the accelerating voltage and on the band width.

As it can be seen in Figure 2 there is a trade-off between the accelerating voltage and the bandwidth of the cavity. From the accelerating voltage point of view the optimum value for coupling constant is the critical coupling where β is one and there is no power reflected from the cavity to the coupler. On the other hand to increase the bandwidth one should make β as large as possible. According to the desired values for the accelerating voltage and the bandwidth, adjusting the coupling constant to a value between 3.5 and 4.5 seems to be the best choice [3].

The input power is coupled to the cavity using a loop which is shown in Figure 3. This loop actually excites a magnetic dipole inside the cavity. The magnitude of this dipole is proportional to the area of the loop and also to the input power of the feedthrough and the amplitude of the mode that it excites is proportional to the scalar product between the magnetic dipole moment of the loop ($\vec{M}$) and the magnetic field of the corresponding mode inside the loop ($\vec{B}$) [4]:

$$|E| \propto \vec{M} \cdot \vec{B} \quad . \tag{3}$$

Based on the above equation one can vary the coupling constant by changing the loop orientation. This can be another advantage of using loop coupling instead of a waveguide coupler. One can change the coupling constant between the coupler and the cavity by changing the area of the loop (changing $\vec{M}$), moving it up or down (changing $\vec{B}$) or even by changing its orientation (changing the angle between $\vec{M}$ and $\vec{B}$).

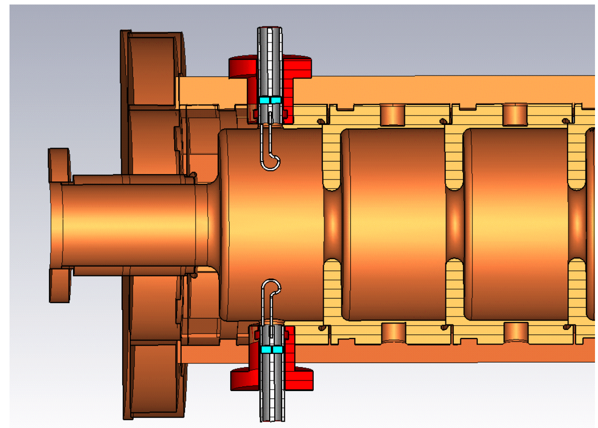

Figure 3: Cross sectional view of the cavity with its two input loops.

Based on the simulation results it is difficult to achieve a high coupling constant (more than 3) with only one loop. The solution to this problem is using two loops opposite to each other. This design would also be better because of the improved symmetry of the cavity, that means the more symmetric pattern of the electric and magnetic field inside the first cell. Figure 3 shows the two input loops of the cavity.

THERMAL SIMULATION

One of the phenomena that might affect the precision of the cavity operation is increasing the temperature of different parts specially the coupler during the operation. Therefore in order to determine if it is feasible to use such feedthroughs to couple the power into the cavity, one should find the temperature distribution during the operation of the cavity. The electric and magnetic field inside the cavity and the thermal losses of different parts of the cavity and the coupler lead to a heat generation and consequently the temperature of different parts of the cavity increases. Thermal simulation can be operated using CST Mphysics Studio, the Thermal solver. This solver uses the thermal losses which is calculated by CST Microwave Studio. Also one should define thermal surface properties of different parts i.e. their emissivities. Since the input power is pulsed with 890 W and 1% duty cycle, the power scaling factor should be adjusted to have a total power of 8.9 W. The cooling water is assumed as a perfect thermal conductor whose temperature is equal to the operation temperature. The simulated temperature of the different parts of the cavity is displayed in Figure 4 while Figure 5 shows the temperature of the feedthrough and the loop clearer. The operating temperature in this simulation is assumed to be 20°C. A higher operating temperature will not change the temperature distribution and just adds an offset to the temperature of all parts. As it can be observed the maximum

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temperature of the feedthrough is about 70°C which is completely tolerable for the feedthrough since according to its provider claims the upper limit for the operating temperature of this feedthrough is 300°C. One should note that the input power which is considered for this simulation is the maximum power that will be injected to the cavity in the worst case of the arrival time ±150 fs. Since in the real operation the arrival time jitter is not always the maximum, the input power and consequently the temperature of the feedthrough and its loop would be lower than the simulation value.
By increasing the temperature of the loop from 20° C to 70°C, because of thermal expansion the size of the loop will change slightly which changes the coupling constant from 4.13 at 20° C to 4.11 at 70°C. This leads to a change in accelerating voltage by maximum 50 V. This change of the accelerating voltage can lead to an error of less than 0.2 fs in the arrival time fo the electron bunches.

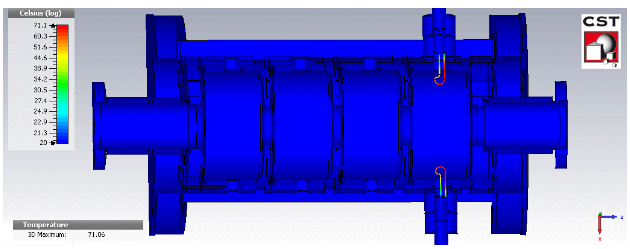

Figure 4: Temperature distribution of the cavity for 8.9 W average power.

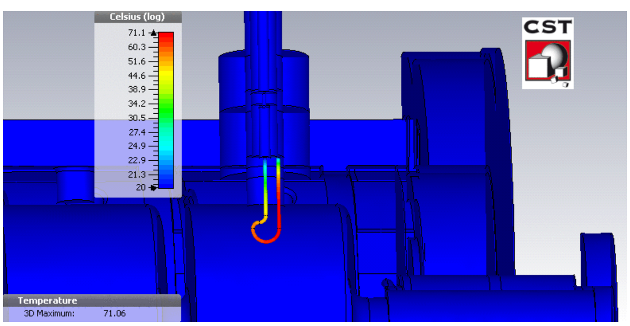

Figure 5: Temperature distribution of the loop and feedthrough.

Figure 6 shows the temperature of the feedthrough and loop if only one loop is used to couple the input power to the cavity. In this situation the temperature of the loop may increase up to 200°C which is not a secure value. Furthermore, 200°C increase in the temperature of the loop changes the coupling constant from 4.13 to 3.95 which in turn varies the accelerating voltage of the cavity up to 300 V. This amount

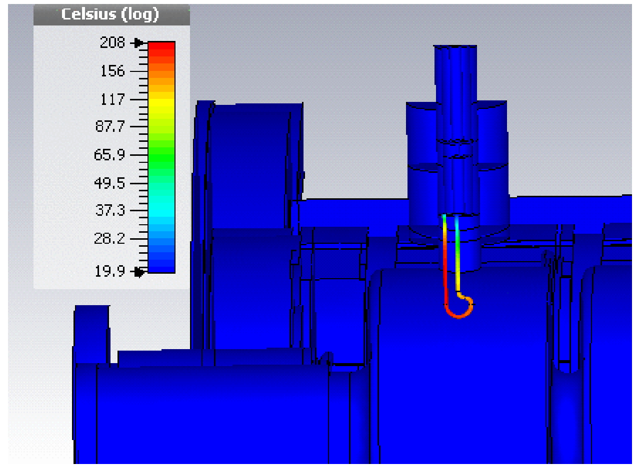

Figure 6: Temperature distribution of the loop and feedthrough when one loop is used.

of variation in the accelerating voltage leads more than 1 fs error in the arrival time of the electron bunches that is not a tolerable error. The thermal stability is therefore one of the other reasons that two input loops are being used.

CONCLUSION

A normal conducting cavity has been designed to correct the arrival time jitter at FLASH. The input power is going to be injected via two loops. Thermal studies has been performed to find the temperature distribution of different parts of the cavity and the coupler. According to the results the arrival time error due to the thermal expansion during the operation would be less than 0.2 fs if we use two input loops. However using just one loops leads to an error of more than 1 fs that is not tolerable.

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