Design of a Normal Conducting Cavity for Arrival Time Stabilization at FLASH

Fakhari, M. (DESY) *et al*

03 May 2015

The EuCARD-2 Enhanced European Coordination for Accelerator Research & Development project is co-funded by the partners and the European Commission under Capacities 7th Framework Programme, Grant Agreement 312453.

This work is part of EuCARD-2 Work Package **13: Novel Acceleration Techniques (ANAC2)**.

DESIGN OF A NORMAL CONDUCTING CAVITY FOR ARRIVAL TIME STABILIZATION AT FLASH*

M. Fakhari†, K. Floettmann, S. Pfeiffer, H. Schlarb, DESY, Hamburg, Germany
J. Rossbach, Uni HH, Hamburg, Germany

Abstract

It has been shown, that beam-based feedback loops stabilize the bunch arrival time in the femtoseconds range. However, further minimizing the bunch arrival time jitter requires a faster actuator that is a normal conducting cavity with higher bandwidth compared to narrow-band superconducting cavities. We present the design of a 4-cell normal conducting cavity that is going to be used in a fast beam-based feedback at free-electron laser FLASH at Hamburg. The input power will be injected to the cavity via a loop coupler from the side of the first cell. The operating frequency of the designed cavity is about 3 GHz with an adjustable bandwidth. The long range longitudinal wakefield calculation results are reported to investigate the cavity performance for multi-beam operation up to 3 MHz bunch repetition rate. The results declare that the influence of the long range wakefield on the arrival time jitter is less than 1 fs.

INTRODUCTION

The Free-Electron Laser FLASH at Hamburg provides short laser pulses to study the dynamics of molecular and chemical reaction on an atomic level. To generate the ultra short wavelength laser pulses, a high-quality electron beam is accelerated in superconducting cavities to an energy of 1.25 GeV and then sent through long magnetic undulators. The short wavelength laser light is used e.g. to study the temporal dynamics of matter typically carried out in a pump-probe arrangement, where atoms or molecules are excited by an external ultra-short pulse optical laser while their reactions are visualized using the FEL light. To achieve the required femtosecond resolution a precise regulation of bunch arrival time within a train of electron bunches is mandatory. For FEL users, it is therefore essential that the arrival time of the individual radiation pulses have a stability with a precision of a few femtoseconds only. Three superconducting accelerating modules, ACC1, ACC39 and ACC23, are being used to adjust the arrival time of the bunches [1]. However, since these modules are narrow bandwidth caused by their high quality factor, it takes a non-negligible time to stabilize the arrival time. Furthermore the final arrival time has a jitter of ± 150 fs peak to peak. Further minimizing the bunch arrival time jitter requires faster actuator, e.g. a normal conducting cavity with higher bandwidth compared to the narrow-band superconducting cavities. A normal conducting cavity is thus designed for this purpose. This cavity is going to be installed at FLASH main linac as shown in Fig. 1. Concerning the space limitation in FLASH a side coupling to this cavity is required. Since the input power of the cavity is less than 1kW 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 sate amplifier with a coaxial cable as the output it would be easier to connect its output directly to a feedthrough instead of using a coaxial to waveguide converter. In this paper the designing process and the simulation results for the designed cavity are presented. The long range wakefield in the designed cavity has also been investigated to make sure that the desired arrival time resolution is achievable.

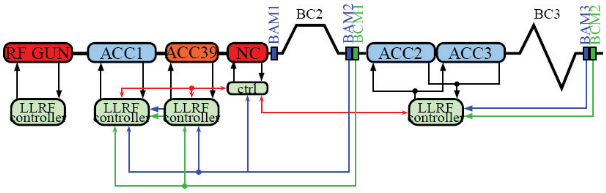

Figure 1: Place of installation of the NC cavity at FLASH

DESIGNING PROCESS

In order to design the fast feedback cavity, the arrival time deviation $\Delta t_A \approx \pm$ 150 fs (peak-peak) needs to be corrected. This requires an energy correction of:

$$\Delta E = \frac{\Delta t_A \cdot c}{-R_{56}} \cdot E \approx \pm 37.5 \text{ keV} \tag{1}$$

where c is the speed of the light in free space, R_{56} is the bunch compressor parameter which is -0.18 m at FLASH-BC2, and the electron energy E is about 150 MeV. To achieve the required energy correction an accelerating voltage of $V_{acc} = \Delta E/e \approx 37.5$ kV is needed. Furthermore, a half bandwidth of 400 - 500 kHz is expected in order to make the cavity fast enough. The designed cavity is formed from four coupled pillbox cavities and has four fundamental TM_{010} normal modes which are named as 0-Mode, $\frac{\pi}{3}$-mode, $\frac{2\pi}{3}$-mode, and π-mode. These names are based on the phase shifts between adjacent cells. The operating mode is the π-mode with the frequency of 2998 MHz. After designing the cells of the cavity the most important part is to design its input coupler. By changing the coupling constant one can change the external quality factor and subsequently the bandwidth of the cavity. However, by changing the coupling constant the accelerating voltage also varies. For a cavity

---

[*] Work supported by the European Commission under the EuCARD-2 FP7 Research Infrastructures grant agreement no. 312453

[†] moein.fakhari@desy.de

with the effective shunt impedance r, input power P_{in}, and the coupling constant β the accelerating voltage can be written as follow [2]:

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

On the other hand the bandwidth of a cavity can be written as a function of the resonant frequency f_r, the unloaded quality factor Q_0, and the coupling constant β:

$$f_{1/2} = \frac{f_r}{2Q_L} = (1+\beta)\frac{f_r}{2Q_0} \qquad (2)$$

For the designed cavity the unloaded quality factor is about 16000 and the effective shunt impedance is about 8 MΩ. Considering the peak value of 890 W for the output of the preamplifier which is going to supply the input power for the cavity, the accelerating voltage and the bandwidth of the cavity are shown in Fig. 2 as functions of the coupling constant.

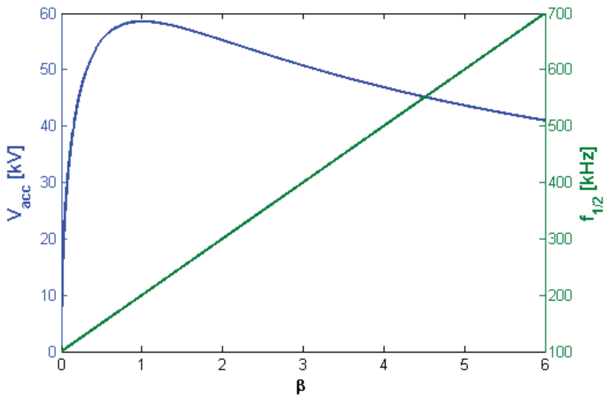

Figure 2: Influence of the coupling constant on the accelerating voltage and the bandwidth

Input Coupler

As it can be seen in Fig. 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 the coupling constant is the critical coupling where β is equal to unity 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 around 4 seems to be the best choice.

As it was described a side coupling is required for the cavity. A feedthrough should be installed on the body of one of the cavity cells while the input power is coupled to the cavity using a loop which actually excites the electromagnetic fields inside the cavity. The magnitude of the excited field is proportional to the scalar product of the magnetic dipole of the loop and the magnetic flux that passes through the loop. It is therefore possible to vary the coupling constant by changing the loop size, its position and also its orientation. This can be another advantage of using loop coupling instead of a waveguide coupler.

Based on the simulation results it is not possible to achieve a high coupling constant (more than 3) with only one loop. The reason is that by increasing the size of the loop the total length of the loop will be comparable with the operating wavelength. Hence, it is not correct to assume a constant current for the loop. The best assumption for the loop current would be a sinusoidal distribution like standing wave distribution [3]. The solution to this problem is using two loops opposite to each other. This design would also be better considering the higher symmetry of the cavity. Fig. 3 shows the cross sectional view of the cavity. The input loops of the cavity as well as the cooling tubes and the tuning knobs are also shown in this figure.

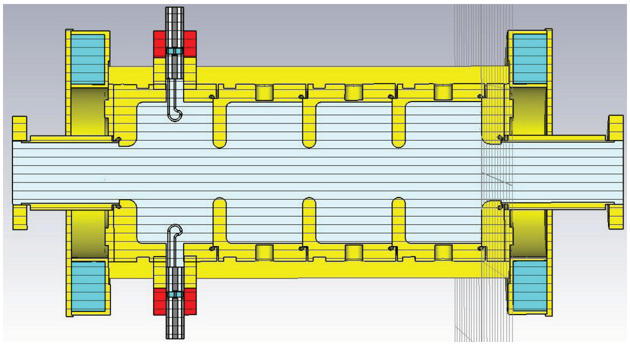

Figure 3: Cross sectional view of two input loops inside the cavity

Simulation Results

The cavity is designed and simulated using CST Microwave Studio. The simulation results for the designed cavity are summarized in Table 1. The accelerating voltage given in this table is based on the maximum value of the input power which is 890 W.

Table 1: Simulation Results for the Cavity

Parameter	Simulated value
$\pi - mode$	2998 MHz
$\frac{2\pi}{3} - mode$	2989 MHz
$\frac{\pi}{3} - mode$	2971 MHz
$0 - mode$	2954 MHz
Unloaded Quality factor (Q_0)	16000
Loaded Quality factor (Q_L)	3100
Accelerating voltage (V_{acc})	49 keV
Half bandwidth ($f_{\frac{1}{2}}$)	480 kHz

WAKEFIELD EVALUATION

The designed cavity is required to correct the arrival time of the bunches with a resolution in femtosecond level. It

ISBN 978-3-95450-168-7

seems therefore to be necessary to study the long range wakefield in the cavity to make sure that the desired resolution is achievable. When a charged bunch passes trough the cavity, it will excite the fundamental mode as well as the higher order modes of the cavity. The electric field inside the cavity which will be sum of the different modes is called wakefield. The high frequency components which frequency is above the cutoff frequency of the beam pipe can propagate away along the beam pipe and do not remain localized. But the lower frequency modes, below the cutoff frequency of the pipe remain localized and can affect the particles in the same bunch (short range wake field) as well as the particles in the trailing bunch (long range wake field). To evaluate the wakefields, a parameter named loss factor is defined for each mode of the cavity which determines the amplitude of the electric field that is excited by the beam [4]:

$$k_m = \frac{V_m^2}{4U_m} \tag{3}$$

where V_m is the voltage corresponding to mode m, and U_m is the stored energy in the electromagnetic field of this mode. One can find the wakefield by summing the contribution of all individual modes. For example the longitudinal delta wake potential for a distance s behind the bunch can be calculated from the following equation [4]:

$$W_{\parallel}^{\delta}(s) = \sum_{m} 2k_{\parallel_m} \cdot cos\left(\omega_m \frac{s}{c}\right) \cdot exp\left(-\frac{\omega_m}{2Q_m}\frac{s}{c}\right) \tag{4}$$

where $W_{\parallel}^{\delta}$ means the longitudinal wake potential caused by a charged particle with δ-function distribution. This delta function can be used as a Green's Function to calculate the wake potential from any given charge distribution. In this equations m is the index of the modes which have a longitudinal component of the electric field on the axis. In order to evaluate the longitudinal and transverse wakefields for the cavity its higher order modes (HOMs) are simulated by CST up to the cut-off frequency of the beam pipe. It should be noted that monopole modes are the dominant modes in determining the longitudinal wakefield while the transverse wakefield is affected mostly by the dipole modes. From the HOMs longitudinal and transverse wakefields are calculated as Fig. 4 and Fig. 5 respectively for a Gaussian distributed bunch with a bunch length of 2mm. Longitudinal and transverse wakefield can also be determined directly by simulation with CST Particle Studio. Such simulation has been performed for the same bunch and the results are shown in Fig. 6 and 7.

There is a little difference between the simulation and calculation results. The reason can be the limited number of the HOMs which are considered to calculate the wake potential. As it can be seen from the both groups of the figures, the longitudinal wakefield inside the cavity is about 0.2 V/pC while 300 ns is elapsed after the first bunch, when the trailing bunch is arriving (assuming 3MHz bunch frequency at FLASH). Therefore for 1 nC bunch charge, the long range longitudinal wakefield will be 0.2 kV. This wakefield can change the arrival time of the bunch by less than 1 fs which is acceptable for our requirements.

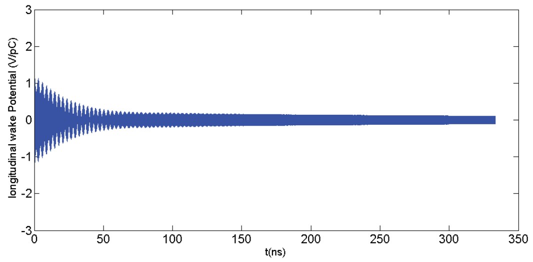

Figure 4: Longitudinal wakefield calculated from the HOMs

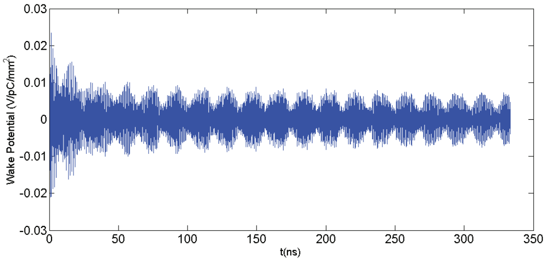

Figure 5: Transverse wakefield calculated from the HOMs

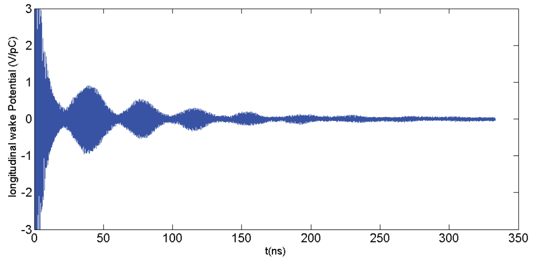

Figure 6: Longitudinal wakefield simulated with CST

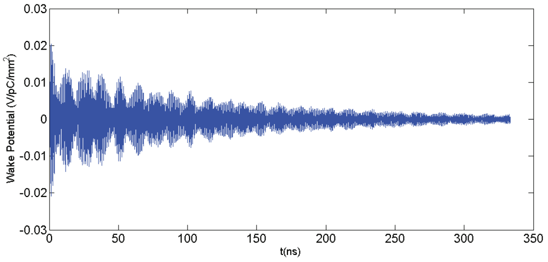

Figure 7: Transverse wakefield simulated with CST

CONCLUSION

An ultra fast normal conducting RF cavity is designed to reduce the arrival time jitter to femtosecond level. The designed cavity will provide an accelerating voltage of 49 keV with half bandwidth of 480 kHz which are enough in order to stabilize the arrival time of the bunches. Wakefield evaluations show that the effect of the wakefields from HOMs leads to a jitter of less than 1 fs which is negligible.

REFERENCES

[1] S. Pfeiffer et al., "Fast Feedback Strategies for Longitudinal Beam Stabilization", IPAC'12, New Orleans, USA, May 2012.

[2] T. Wangler, *RF linear Accelerators*, John Wiley & Sons Inc, 1988.

[3] R.E. Collin, *Foundation for microwave engineering*, John Wiley & Sons Inc, 2nd edition, 2007.

[4] A.W. Chao, *Physics of Collective Beam Instabilities in High Energy Accelerators* , John Wiley & Sons Inc, 1993.