Power losses caused by longitudinal HOMs in 3.9 GHz SHINE cryomodule

Junjie Guo\textsuperscript{1,2}, Qiang Gu\textsuperscript{2,3,*}, Jianhao Tan\textsuperscript{2,3}, Zhen Wang\textsuperscript{3}

1 University of Chinese Academy of Sciences, Beijing, China
2 Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai, China
3 Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai, China

E-mail: guqiang@sinap.ac.cn

Abstract. Shanghai high repetition-rate XFEL and extreme light facility (SHINE), the first hard XFEL based on a superconducting accelerated structure in China, is now under development at the Shanghai Institute of Applied Physics, Chinese Academy of Sciences. In this paper, power losses caused by trapped longitudinal high order modes (HOM) and steady-state loss generated by untrapped HOMs in 3.9 GHz SHINE cryomodule will be investigated and calculated. Results are presented for power losses of every element in 3.9 GHz cryomodule, caused by HOM excitation in the acceleration RF system of the continuous-wave (CW) linac of SHINE.

1. Introduction

In the future, SHINE will provide hard coherent X-ray radiation for a broad spectrum of basic research applications \cite{1, 2}. Superconducting RF (SRF) technology has been chosen in order to minimize power consumption and operational cost of the facility, because SHINE is required to operate in continuous wave (CW) regime.

While the use of superconducting accelerating cavities in large particle accelerator facilities offers many advantages in areas such as RF efficiency and feasible beam parameter ranges, a major expense of operating such a machine is the power required of the cryogenic plant. Consideration must be given to minimizing both static and dynamic heat loads. One element of the latter, particularly relevant in a high-current, short bunch, CW facility, is higher-order-mode (HOM) electromagnetic field power generated by the beam in passing through the cavities and beamline elements. Therefore, power of losses generated by HOMs due to monopole modes are the subject of calculations.

3.9 GHz cryomodule of SHINE is considered, which contains beam line interconnections (bellows, gate valves and beam line absorber) shown in Fig. 1 \cite{3}. The 3.9 GHz cryomodule of SHINE comprises eight 9-cell cavities, each with active length 346 mm, which has 15 mm iris radius and 20 mm beam tubes radius. Between the cavities are bellows that are roughly 5 cm long and have 13 convolutions.

Two cases of the beam in the SHINE are considered in this paper. Case 1 is that the bunch repetition frequency is assumed to be constant and equal to 1 MHz, and total charge $Q_b = 300 \text{ pC}$, and the bunch length is 3 mm. Case 2 is that the bunch repetition frequency is assumed to be constant and equal to 0.6 MHz, and total charge $Q_b = 100 \text{ pC}$, and the bunch length is 1 mm.
2. TRAPPED LONGITUDINAL HOM

Electro-magnetic field will be excited by the bunch behind it, when the electron bunch pass through the cavity. This electromagnetic field is called wakefield in time domain, High Order Mode in frequency domain, which can be divided into longitudinal and transverse HOMs according to the component on the coordinate axis. Power losses of every element in 3.9 GHz cryomodule is mainly caused by longitudinal HOMs, which is our main research object in this paper. Longitudinal HOM can be characterized as trapped or untrapped HOM by their relation to the beam pipe cut-off frequency. Frequency of the trapped HOMs is below $f_{\text{cutoff}}$, while the untrapped HOMs have frequency above $f_{\text{cutoff}}$. This section focuses on trapped HOM, and un-trapped HOM will be considered in the next section.

As we known, trapped longitudinal HOM below the beam pipe cut-off frequency of third harmonic SRF cavities causes heat and adds to the cryogenic losses and increases operational cost of the linac, which is excited when beam traverses the SRF cavity. Interaction of the beam spectrum with cavity HOM spectrum will lead to power loss of SRF cavity.

The main contribution of HOM loss comes from the frequency mode with the highest impedance mode and frequency approaching the main line of the beam spectrum. HOM spectrum of 3.9 GHz third harmonic cavity is evaluated by using CST simulation [4]. For longitudinal monopole modes the cut-off frequency in a cylindrical pipe is defined as $f_{\text{cutoff}} = \frac{2\pi c X_{01}}{r} \approx 2\pi c \frac{2.4048}{r}$, where $X_{01}$ is the first root of $J_0(r)$ the Bessel function of the first kind of order 0. According to the above formula, the cut-off frequency of 3.9 GHz third harmonic cavity is equal to 5.74 GHz. And spectrum and R/Q of 3.9 GHz third harmonic cavity are shown in Fig. 2.

The beam traversing through a cavity excites various modes of the cavity. The main accelerating mode will be compensated, but there are also high order modes (HOM) in the cavity. Excitation of HOMs leads to losses of beam power. And it is necessary to know which modes are used to evaluate these losses. As we know shapes of cavities, all needed information can be obtained by using CST simulation. After that power losses would be calculated as it is described below.

According to Ref. [5], Surface resistance of superconducting Nb is

$$R_s = R_{\text{res}} + R_{\text{BCS}}$$  \hspace{1cm} (1)

where $R_{\text{res}} = 10 \, n\Omega$, and BCS part is parameterized as

$$R_{\text{BCS}}[\Omega] = 2 \times 10^{-4} \ \frac{1}{T[K]} \left( \frac{f_n[GHz]}{1.5} \right)^2 e^{-17.67/T[K]}$$  \hspace{1cm} (2)
Trapped modes may have higher value of $Q_h$, where $Q_h$ is the loaded quality factor of HOMs. The following $Q_h$ values are used in our analysis: $Q_h = 2 \times 10^5, 10^6, 10^7$. HOM frequency spread due to manufacturing mechanical tolerances will be considered in our simulation. And total power loss in the cavity walls is calculated as sum of losses by individual beam harmonics.

Power of losses can be calculated as \[ P = \sum_{n=1}^{N} \sum_{m=1}^{M} \left( \frac{1}{8W_0} \right) \times \left( \frac{R}{Q} \right) \frac{\bar{I}_n R_s \omega_m^3 A_{mm}}{m (\omega_n^2 - \omega_m^2)^2 + \left( \frac{\omega_n \omega_m}{Q_h} \right)^2} \] (3)

where

\[ A_{mm} = \oint H_m^2(z)ds = \int_0^L 2\pi r(l)H_m^2(l)dl \] (4)

To accurately estimate the probability of resonance HOM excitation in a SHINE linear accelerator by the beam component, a statistical analysis must be carried out, which requires the propagation of the data for HOM parameters (frequency, impedance and quality factor). So manufacturing mechanical tolerances will be taken into account to obtain these information. Acceleration mode is supposed to be perfectly adjusted so its frequency exactly 3.9 GHz are used in calculations respectively. About 3000 random runs are made for each cavity in order to estimate probability of the RF losses per cryomodule [7]. Distribution of power loss about two Beam Cases in 3.9 GHz third harmonic cavity are shown in Fig. 3

3. UNTRAPPED LONGITUDINAL HOM

As mentioned in the previous section, longitudinal HOM above cut-off frequency is called untrapped longitudinal HOM, which can propagate through the cryomodule. And it will cause the heat load of every element of the cryomodule like cavity, bellows, beam line absorber (BLA), fundamental power coupler (FPC), High Order Mode Coupler (HOMC), Gate Valve, flange and Cryomodule (CM) pipe. In this section, power losses caused by untrapped longitudinal HOM will be considered and calculated together.

When electron bunch traverses through the 3.9 GHz cryomodule shown in Fig. 1, its wake energy is radiated into modes (un-trapped longitudinal HOMs) that are much above cut off frequency. The primary source of excitation of untrapped longitudinal HOMs in the SHINE is irises of 9-cell cavities (called geometrics wake).

HOM power generated by beam is:

\[ P = Q^2 f_{rep} K_{loss} \] (5)
Figure 3. Calculations of the power losses in the 3.9 GHz third harmonic cavity of Case 1 (a) and Case 2 (b)

In the SHINE, maximum HOMs power is generated for Case \( Q_b = 300 \text{ pC} \) and \( f_{\text{rep}} = 1 \text{ MHz} \) and minimum HOMs power is generated for Case \( Q_b = 100 \text{ pC} \) and \( f_{\text{rep}} = 0.6 \text{ MHz} \). So the above two cases will be considered in this section.

According to Eq. (5), we need \( K_{\text{loss}} \) this parameter. Actually, \( K_{\text{loss}} \) is defined by the following equation:

\[
K_{\text{loss}} = \frac{1}{q} \int_{-\infty}^{\infty} W_{\|}(s) \lambda(s) ds
\]

where \( q \) is bunch charge, \( W_{\|}(s) \) is longitudinal wake potential and \( \lambda(s) \) is bunch distribution, usually gaussian distribution [8].

Longitudinal wake potential is a convolution of longitudinal wake function and bunch distribution, as described in the following equation:

\[
W_{\|}(s) = \frac{1}{q} \int_{-\infty}^{\infty} w_{\|}(s - s') \lambda(s') ds'
\]

where \( w_{\|}(s) \) is wake function of a point like charge.

The 3.9 GHz SHINE linac can be considered as multi-periodic structure: the first elementary period is the cavity cell, the second one is the 9-cell cavity with bellow and beam tubes and the third one is the cryomodule, housing 8 cavities with 9 bellows. Analytical approximation for the point longitudinal wake function [3] can be derived based on ECHO [9]:

\[
w_{\|}(s) = -H(s)(784 \times \exp(-\sqrt{\frac{s}{8.4 \times 10^{-4}}} + 0.9 \cos(5830 \times s^{0.83}) + 1098 \times \delta(s)), [V/pc]
\]

When the beam enters the first cryomodule in a string, it will first encounter transient wakefields that will gradually change to the steady-state wakes. The change occurs over a distance on the order of the catch-up distance, \( Z_{\text{cu}} = a^2/2\sigma_z \). For SHINE, the catch-up distance, \( Z_{\text{cu}} = 0.0375 \text{ m} \) and \( Z_{\text{cu}} = 0.11 \text{ m} \) in the HL section for Beam Case 1 and Beam Case 2 respectively. According to Fig. 1, the length of a 3.9 GHz cryomodule is about 5 m. To reach steady-state solution, one cryomodule need to be considered in HL section for Beam Case 1 and Beam Case 2 respectively. Therefore, wake function is fitted by calculating wake potentials of different \( \sigma_z \) bunch in one cryomodule with ECHO.

With above wake potential, \( K_{\text{loss}} \) can be calculated according to Eq. (6). For RMS bunch length of 1mm in HL, loss factor is 135 V/pC per cryomodule. Steady-state HOM power generated for \( Q_b = 100 \text{ pC} \) and \( f_{\text{rep}} = 0.6 \text{ MHz} \) (Beam Case 2), is 0.81 W/CM.
For RMS bunch length of 3 mm in HL for Beam Case 1, loss factor is 76 V/pC per cryomodule. Steady-state HOM power generated for $Q_b = 300 \ pC$ and $f_{rep} = 1 \ MHz$ (Beam Case 1) is 6.84 W/CM.

In order to understand distribution of power among the modes, HOM power spectrum can be evaluated using the following equation [10]:

$$\frac{dP}{d\omega} = Q_b^2 f_{rep} Z_\parallel(\omega) \exp\left(-\left(\frac{\omega \sigma_z}{c}\right)^2\right)$$ (9)

where $Z_\parallel$ is longitudinal wake impedance. $Z_\parallel$ can be obtained by performing a Fourier transform on wake function. Fig. 4 shows differential HOMs power spectrum about Beam Case 1 and Case 2 in 3.9 GHz cryomodule of SHINE linac.

A frequency range of excited modes can be approximated as:

$$\omega \approx \frac{c}{\sigma_z}$$ (10)

in SHINE linac, bunch length is as short as 1 mm and spectrum of HOMs frequency extends up to 48 GHz. In order to estimate fraction of HOMs power dissipating at 2 K in the cryomodule, the total HOMs power can be deposited as sum of two parts i.e.,

$$P_{total} = \int_0^{\omega_c} \frac{dP}{d\omega} d\omega + \int_{\omega_c}^{\omega} \frac{dP}{d\omega} d\omega$$ (11)

where first term is comprised of power below the cut-off frequency ($\omega_c$) and, this power is effectively extracted out from the operating environment using HOMs couplers. The second term in Eq. (11) corresponds to HOMs that have frequencies above cut-off frequency, which is called as un-trapped HOM power. According to Eq. (9) and (11), un-trapped HOM power of Beam Case 1 can be obtained in HL, which is 4.88 W/CM. Similarly, un-trapped HOM power of Beam Case 2 can be obtained in HL, which is 0.68 W/CM.

Figure 4. Geometry of the 3.9 GHz third harmonic cavity cryomodule with bellows and interconnections.

A way to estimate the distribution of HOM power absorption is to use a diffusion-like model [10], in which the radiation fills the available volume like gas. This way is a good approximation well above cut-off and where the surface reflection coefficient is close to unity.

Power absorption is proportional to impedance of element:

$$I_{abs}^i(\omega) \approx n_i S_i \frac{dP(\omega)}{d\omega} Re(Z_i(\omega)) d\omega$$ (12)
where \( S_{i} \): Surface area of ith element, i is type of element such as cavity, bellows, beam pipe etc; n: no of elements, \( \omega \): angular frequency, \( dP(\omega)/d\omega \): HOM spectral density, \( \text{Re}(Z_{i}(\omega)) \): real part of surface impedance [3].

Power absorbed by ith type element is

\[
P_{i} = \int_{0}^{\infty} \frac{dP}{d\omega} \left( \sum_{i} I_{\text{abs}}^{i}(\omega) \right) d\omega
\]  

(13)

Using Eq. (12) and (13), dependance of surface impedance on frequency and HOMs differential power spectrum, distribution of total power losses is shown in Fig. 5 about Beam Case 1 and Case 2.

![Figure 5. Distribution of total power losses in the 3.9 GHz SHINE cryomodule for Beam Case 1 (a) and Beam Case 2 (b)](image)

4. CONCLUSION
In SHINE linac, based on superconducting accelerated structure, power losses generated by the beam passing through the linac may not be negligible. Therefore, power losses caused by the beam and deposited on each elements of the linac are what we studied in this paper.

Power losses generated by the beam is contribution of longitudinal HOM excited by irises of 9-cell cavities and resistive wall wake of beam pipe. And longitudinal HOM can be characterized as trapped HOM (below cut-off frequency) or untrapped HOM (above cut-off frequency) according to the cut-off frequency of beam pipe. Because it is below cut-off frequency of the beam pipe, trapped HOM can only remain in the cavity, causing power losses of the cavity. Untrapped HOM causes the power losses of every elements of SHINE 3.9 GHz third harmonic cryomodule because it can propagate through the cryomodule.

From the results of trapped HOM section, it is concluded that power losses about two Beam Cases due to resonance excitation of longitudinal monopole HOM are very small. The median power loss, which corresponds to probability of 0.5, is approximately 1 \( \mu W \) for trapped modes of 3.9 GHz third harmonic cavity in Case 1. Once in a while, due to random variation of its frequency, a single HOM in one cavity may come close to resonance. In this case power losses in 3.9 GHz third harmonic cavity may increase up to 100 mW, although probability of such event is extremely low, it is less than 1 mW. Comparing Case 1 and Case 2, we can conclude that the lower \( Q_b \) and \( f_{\text{rep}} \) of the bunch, the smaller the power losses.

From the results of untrapped HOM section, steady-state losses generated by untrapped HOM in HL part are estimated. We find that most of power will be absorbed by beam line absorber. They provide us some confidence in the effectiveness of the beamline HOM absorbers, suggesting that no more than a few percent of this power will present added load to the 2 K cryogenics system.
Based on this study, these calculations will provide a reliable basis for the future construction of SHINE linac.

5. ACKNOWLEDGMENT
We are grateful to Prof. Vyacheslav Yakovlev of Fermilab and Prof. Igor Zagorodnov of DESY. They help me a lot and provide me lots of suggestions. And we are also grateful to many other staff members at the LINAC group of FEL department SINAP for their supports with ideals and discussions.

References
[1] Zhiyuan Z et al 2018 SCLF: AN 8-GEV CW SCRF LINAC-BASED X-RAY FEL FACILITY IN SHANGHAI, in Proceedings of the FEL2017 Santa Fe NM USA, pp 182-184
[2] Zhen W et al 2017 Generation of double pulses at the Shanghai soft X-ray free electron laser facility Nucl. Sci. Tech vol.28 no.28
[3] Lunin A et al 2016 Generation and Absorption of the Untrapped Wakefield Radiation in the 3.9 GHz LCLS-II Cryomodule LCLS-II TN-16-06
[4] CST-Computer Simulation Technology, http://www.cst.com.
[5] Padamsee H et al 1998 RF Superconductivity for Accelerators, Wiley, New York
[6] Khabiboulline T et al 2012 RESONANCE EXCITATION OF LONGITUDINAL HIGH ORDER MODES IN PROJECT X LINAC, in Proceedings of IPAC2012, New Orleans, Louisiana, USA, WEPPC054 pp 2336-2338
[7] Sukhanov A et al 2014 High order modes in Project-X linac Nucl. Instrum. Methods Phys Res. A vol. 734 pp 9-22
[8] Palumbo L et al 1994 Wake fields and impedance [J] arXiv: Accelerator Physics
[9] Code ECHO, http://www.desy.de/ zagor
[10] Saini A 2016 et al RF Losses in 1.3GHz Cryomodule of the LCLS II Superconducting CW Linac [C], in Proceedings of LINAC2016, East Lansing, MI, USA, THPRC014, pp 798-801