HIGHER ORDER MODE DAMPING IN A HIGHER HARMONIC CAVITY FOR THE ADVANCED PHOTON SOURCE UPGRADE *

S.H. Kim#, M.P. Kelly, P.N. Ostroumov, Z.A. Conway, B. Mustapha, G. Waldschmidt, J. Carwardine, G. Decker
ANL, Argonne, IL 60439, USA

Abstract

A superconducting higher-harmonic cavity (HHC) is under development for the Advanced Photon Source Upgrade based on a Multi-Bend Achromat lattice. This cavity will be used to improve the Touschek lifetime and the single bunch current limit by lengthening the beam. A single-cell 1.4 GHz (the 4th harmonic of the main RF) cavity is designed based on the TESLA shape. Two adjustable fundamental mode power couplers are included. The harmonic cavity voltage of 0.84 MV will be driven by the 200 mA beam. The RMS bunch length with the harmonic cavity will be >50 ps. Higher-order modes (HOM) must be extracted and damped. This will be done with two silicon carbide beamline HOM absorbers to minimize heating of RF structures such as the superconducting cavity and/or couplers and suppress possible beam instabilities. The HHC system is designed such that 1) most monopole and dipole HOMs are extracted along the beam pipes and damped in the 'beamline' silicon carbide absorbers and 2) a few HOMs, resulting from introduction of the couplers, are extracted through the coupler and dissipated in a room temperature water-cooled load. We will present time and frequency domain simulation results and discuss damping of HOMs.

INTRODUCTION

We are developing a 4th harmonic cavity for Advanced Photon Source Upgrade (APS-U) at Argonne National Laboratory. It will lengthen the beam bunch so that the Touschek lifetime and single bunch current limit will be improved [1,2]. The cavity is a single-cell 1.4 GHz superconducting cavity scaled from the TESLA shape [3]. Two moveable fundamental mode couplers are employed to separately adjust harmonic voltage and phase in combination with the slow frequency tuner [1,3].

Higher order modes (HOM) excited by relatively high current beams, 200 mA, must be damped. Otherwise, they will cause excessive cryogenic loads and beam instabilities, such as multi-bunch instabilities if resonant with the beam [4]. The damping method here is motivated by the previous work done by Cornell [5,6]. We use an enlarged beam pipe, 104 mm diameter, on the left side of the cavity as shown in Fig. 1 to extract monopole and dipole HOMs; the right side beam pipe is 70 mm, the same as the beam aperture in the cavity. Cavity HOMs propagate along the larger beam pipe and are damped in the 'beamline' silicon carbide HOM absorber which uses Coorstek SC-35 ceramic [6]. The smaller beam pipe on the right side also needs a HOM absorber to damp beam pipe modes and a portion of HOMs excited due to couplers, 'coupler modes'. Several coupler modes must be extracted out through the coupler because they cannot propagate along either beam pipe. However, we found a trapped mode if we use a traditional symmetric antenna for the coaxial coupler, therefore we developed a new coaxial antenna to resolve this issue. Details of this new antenna will be discussed in the next section.

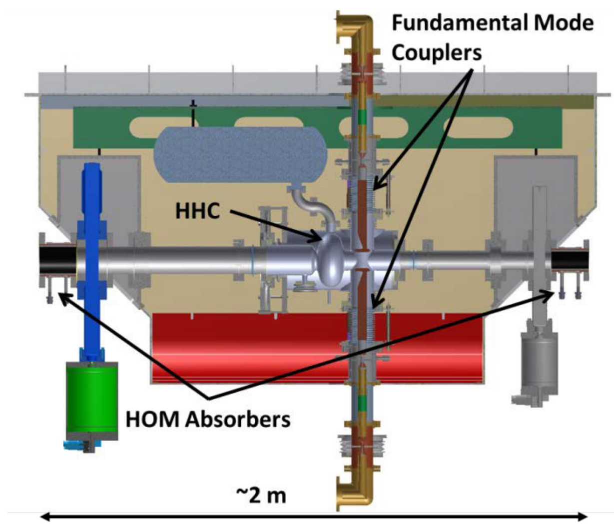

Figure 1: Conceptual model of the HHC cryomodule Details of the beamline HOM absorbers will be presented in [7] and the fundamental mode couplers in [8].

In the later of this paper, we will present monopole dipole impedances simulated using CST Wakefield Solver and cross-checked using CST Eigenmode Solver. HOM induced power losses calculated from the simulated longitudinal impedance will be also discussed. The beam current is 200 mA and currently considering operational modes are uniformly distributed 48 or 324 bunches with no gap in the bunch fill pattern as shown in Table 1.

COUPLER ANTENNA

A trapped mode was found in the initially considered design of the coupler antenna as shown in Fig. 2 (a). The larger profile antenna tip was used in this design for stronger coupling and also for minimizing the geometrical perturbation seen by the beam so that beam impedance is reduced. However, the first TE11-like mode in the coaxial coupler is trapped near the coupler tip, as shown in Fig. 2

*Results in this report are derived from work performed at Argonne National Laboratory. Argonne is operated by UChicago Argonne, LLC, for the U.S. Department of Energy under contract DE-AC02-06CH11357.
#shkim121@anl.gov

ISBN 978-3-95450-178-6

(a) because the mode frequency is less than the cutoff for the TE11 modes in the coaxial coupler. r/Q of this mode is a few Ohms and Q is ~10^4 so beam will lose excessive power (>1 kW) which will be dissipated on the coupler surface such as the center conductor and bellows if beams resonantly excite this mode. Extraction of this mode through beam pipes is not possible either. This mode can be coupled to the TM01 mode in the beam pipe due to the overlapping field distributions in that region. However, the cutoff frequency of the TM01 mode even in the larger beam pipe is 2.3 GHz, much higher than the frequency of this mode.

Table 1: HHC and Beam Parameters Regarding to HOMs

Parameter	Value
Fundamental mode frequency	1.408 GHz
Fundamental mode r/Q*	109 Ohm
Fundamental mode voltage	0.84 MV
Beam pipe diameter**	104/70 mm
Beam current	200 mA
Number of bunches***	48/324
Bunch charge	15.3/2.2 nC
Bunch repetition rate	13/88 MHz
Bunch length	>50 ps

* $r/Q = V^2/\omega U$
** Larger/smaller beam pipes: cavity beam aperture is 70 mm even on the side of the larger beam pipe.
*** Uniformly distributed with no gap in the bunch fill pattern

To extract this mode, we developed a new antenna, as shown in Fig 2 (b). The asymmetrical conical transition allows this mode to be converted to the TEM mode so that it propagates along the rest of the coupler and is damped in the coaxial load. We note our coaxial load, an Altronic 9705, experimentally shows good matching at the frequencies up to ~3 GHz, which is high enough relative to the frequency range of the coupler modes.

Other possibilities for coupler modes were also studied. There exist 1) a coupler TE11-like mode with a polarization perpendicular to the previous one and 2) higher axial (axis of the coaxial line) order modes. The first one is able to be coupled to the beam pipe TE11 mode and its frequency is higher than the TE11 cutoff frequency in the larger beam pipe, 1.68 GHz so it can propagate along the larger beam pipe and be damped in the beamline HOM absorber. Likewise, in the second case, the modes above the TM01 cutoff in the larger beam pipe can also propagate along the larger beam pipe. The remainder of the second type need to be extracted along the coupler. It has been verified that these are well converted to the TEM mode such that Qext is ~10^3 or less.

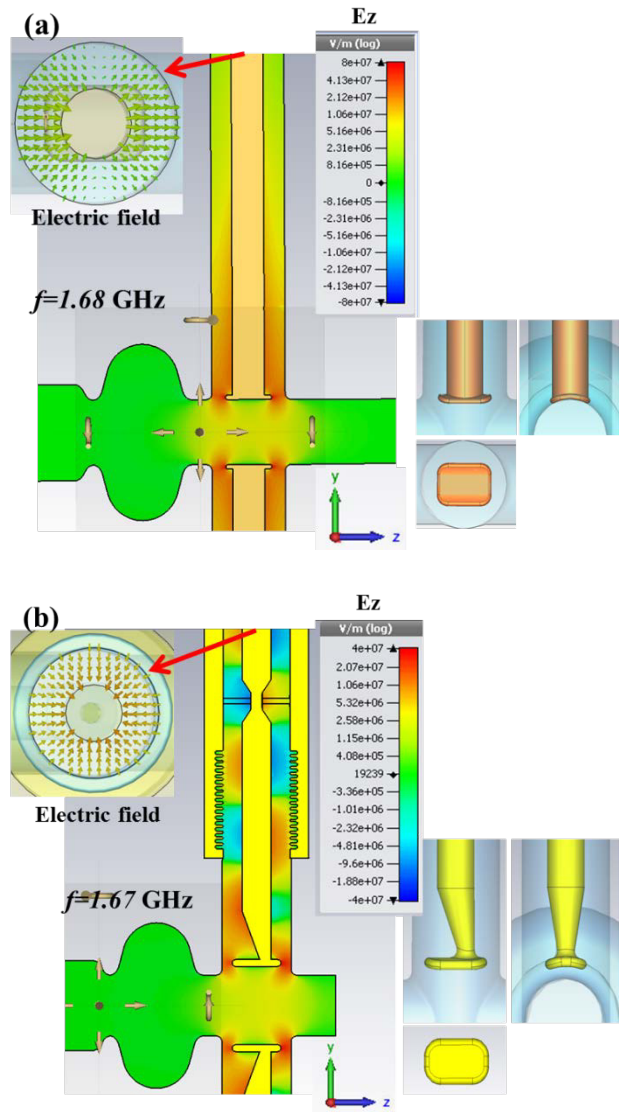

Figure 2: The first coupler mode with two different antennas calculated using the CST Eigenmode Solver. (a): initial design with the symmetric antenna, a TE11-like mode is trapped around coupler tip, (b): modified design with the asymmetric antenna to extract the previously trapped mode out by converting it to TEM mode. This mode can not propagate along the beam pipe so the beam pipe in the right side is reduced for the simulation in the modified design (b).

HOM IMPEDANCE AND LOSS POWER

Wakefield simulations were done using the model as shown in Fig. 3. The couplers are simplified, and the port at the end of the coupler is matched only for the TEM mode; any other higher order modes in the coupler such as the TE11 mode are reflected back at this boundary. Interesting HOMs are monopole and dipole modes from the beam dynamics standpoint [9]. We excite those modes with different sets of drive beam offset and symmetry condition as shown in Fig. 4. The radial beam offsets for the dipole modes are 5 mm from the beam axis, small enough compared with the beam pipe radius such that the dipole field is radially linear and the dipole impedance is independent of the radial offset.

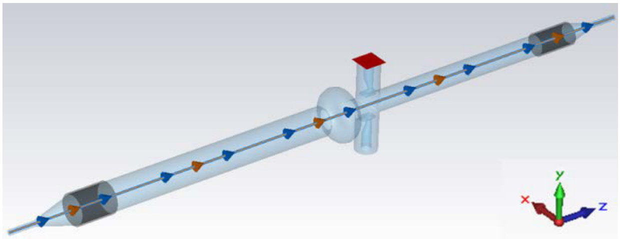

Figure 3: RF model used for wakefield and eigenmode simulations.

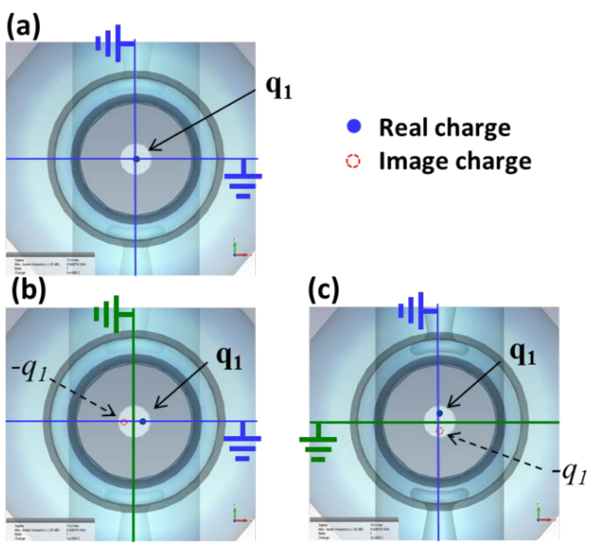

Figure 4: Beam offset and symmetry condition for different modes; (a): monopole, (b): dipole-x, where electric field is normal to y-z plane, (c): dipole-y, where electric field is normal to x-z plane. The ground symbols indicate conditions for symmetry planes; green: 'electric boundary' where electric fields are normal, blue: 'magnetic boundary' where magnetic fields are normal.

The simulation results show the HOM impedances are much lower (~2 orders of magnitude) than the beam instability limit as shown in Fig. 5. For relatively high impedance modes, additional Eigenmode simulations were done. The same model as shown in Fig. 3 was also used for the Eigenmode simulations. The Eigenmode simulation results are in fair agreement with Wakefield simulation as shown in Fig. 5. These results show the coupler mode is well damped as we discussed in the previous section. Likewise, HOMs between ~2 and ~4 GHz are strongly damped. For example, the cavity TM011 mode has r/Q one order of magnitude higher than the cavity TM012 but their impedances are similar to each other. This is because the silicon carbide ring is a relatively broadband resonator. As a result, broadband impedance is relatively high and HOMs are strongly damped in the frequency range of this resonance.

The resolution of the impedance spectrums is 0.2 MHz, achieved by running simulation until the wake length is 1.5 km. This resolution is high enough to resolve most of the HOMs whose Q_L is ~10^3 or less. The probability of missing high Q modes is very low because the sensitivity is sufficient to identify any mode whose Q_L up to ~10^7. Nevertheless, we cross-checked for trapped modes in Eigenmode simulations. The model as shown in Fig. 3 is not appropriate for this search because there are a few thousand eigenmodes existing in frequency range of 1.4 – 6 GHz again because the silicon carbide ring is a relatively broadband resonator. Instead, we used a model with reduced beam pipes cut such that straight sections are ~100/~50 mm long, good enough to show trapped modes in the cavity or couplers if they exist. As a result of the search over all possible eigenmodes, no trapped modes were found.

The power loss due to HOMs is estimated from longitudinal monopole impedance because contribution of any higher azimuthal modes such as dipole modes to the longitudinal impedance is negligible. If an HOM excited by a beam is strongly damped such that it quickly decays before the following bunch comes into the cavity, which can be also represented by $f_b \ll \Delta f_{HOM}$, where f_b: the beam repetition rate, Δf_{HOM}: the bandwidth of the HOM, then the loss power is represented by [10,11]

$$P_{loss} \cong k_{||} q I_0 \,, \tag{1}$$

where q is the single bunch charge, I_0 is the total beam current, and $k_{||}$ is the loss factor, given by

$$k_{||} = \frac{1}{\pi q^2} \int_0^\infty Z(\omega) I^2(\omega) d\omega. \tag{2}$$

Here, ω is the angular frequency of the HOM, $I(\omega) = qF(\omega)$, where $F(\omega)$ is the bunch form factor [10]. The approximation applied in Eqn. (1) is still effective until the beam repetition is almost the same as the HOM bandwidth, $f_b \sim \Delta f_{HOM}$. However, if the beam repetition is much faster than the HOM decay time, $f_b \gg \Delta f_{HOM}$, the HOM resonantly builds up with each bunch and the power loss is modified as follows [10,11]:

$$P_{loss} \cong \frac{r}{Q} Q_L I_0^2 F^2(\omega) \,, \tag{3}$$

where Q_L is the loaded Q of the HOM, r/Q is in 'linac definition', defined by $V^2/\omega U$. In the 48 bunch mode, the repetition rate is comparable to bandwidths of most of the HOMs so the power is estimated to be 1.7 kW according to Eqn. (1). One exception is the cavity TM012 mode which has a narrower bandwidth than the beam repetition but the power loss according to Eqn. (3) is ~50 W, negligible compared with the total power loss. In 324 bunch mode, number of HOMs in the resonant case is increased. However, damping of them is strong enough that the power loss in the resonant case is lower than the non-resonant case. In addition, the loss power due to the broadband HOMs, proportional to the single bunch charge, is a factor of 6.75 lower than the 48 bunch mode.

ISBN 978-3-95450-178-6

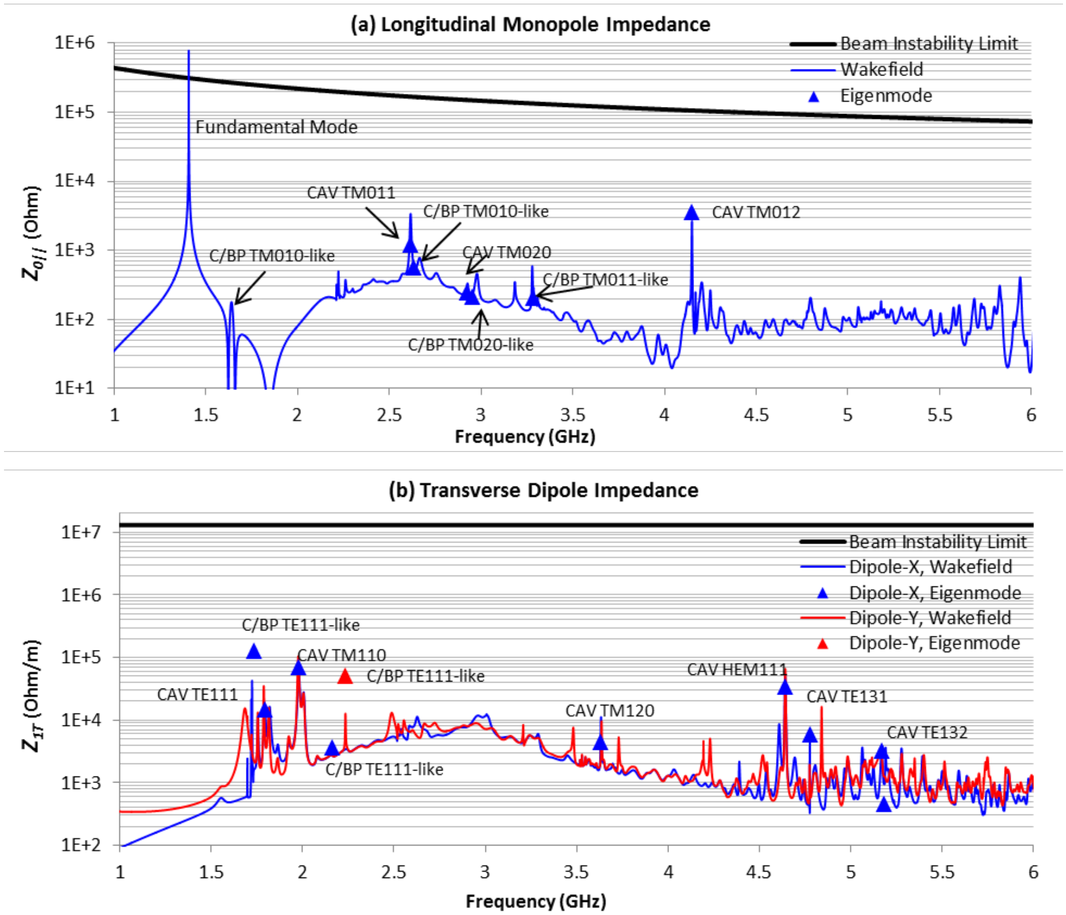

Figure 5: Monopole and dipole impedances calculated in the wakefield and eigenmode simulations. (a): longitudinal impedance for monopole modes, (b): tranverse impedance for dipole modes. The resolution in results of the wakefield simulations is 200 kHz. CAV: cavity, C/BP: coupler and beam pipe.

Therefore, the loss power in the 324 bunch mode will be substantially lower than the 48 bunch mode.

Contributions of the cavity and coupler HOMs to the total power loss is calculated using the electric field profile in the HOM absorbers as a function of time. As a result, their contribution is ~35%. The rest is due to direct interaction of the beam with the silicon carbide rings. Effort to reduce this direct interaction is not practical; for example, if we decrease thickness of silicon carbide ring by half, the power loss is reduced by only 30%, not a substantial benefit in HOM absorber cooling, but the peak impedances become close to the beam instability limit.

SUMMARY

The higher order modes will be damped using the beamline silicon carbide HOM absorbers with the enlarged beam pipe and a newly developed coupler antenna in the higher harmonic cavity for the Advanced Photon Source Upgrade. Wakefield and Eigenmode simulations show the monopole and dipole HOMs are well damped and there are no trapped monopole and dipole HOM in the cavity and couplers.

REFERENCES

[1] S.H. Kim et al., Proc. IPAC2015, p. 1819; http://www.jacow.org

[2] M. Borland et al., Proc. IPAC2015, p. 543; http://www.jacow.org

[3] M.P. Kelly et al., Proc. IPAC2015, p. 3267; http://www.jacow.org

[4] Private communication with L. Emery at ANL.

[5] M. Liepe et al., Proc. SRF2007, p. 9; http://www.jacow.org

[6] R. Eichhorn et al., Proc. IPAC2013, p. 2441; http://www.jacow.org

[7] S.H. Kim et al., THPB073, in this conference SRF2015, Whistler, Canada.

[8] M.P. Kelly et al., THPB088, in this conference SRF2015, Whistler, Canada.

[9] Private communication with M. Borland at ANL.

[10] P.B. Wilson, "Introduction to Wakefield and Wake Potentials," SLAC-PUB-4547 (1989).

[11] M. Furman et al., "Energy Loss of Bunched Beams in SSC RF Cavities," SSC-116 (1987).