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PRECISION CAVITY HIGHER-ORDER MODE TUNING SCHEME FOR STABILIZING THE STORED BEAM IN THE ADVANCED PHOTON SOURCE UPGRADE*

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Abstract

The Advanced Photon Source Upgrade will suffer longitudinal multi-bunch instability because of the presence of several monopole higher-order mode (HOMs) of the 12 352-MHz rf cavities. Even with a feedback system, it would be good to mitigate any driving terms with conventional means such as tuning HOM frequencies with temperature. However the latter is problematic because there will be 90 or so HOMs that are potentially harmful. A scheme is developed, utilizing the measured spectrum of HOMs, to find the best temperature setting for each cavity. We present measurements of 30 or so HOMs, and a thermal model of HOM frequencies using cavity wall power and cooling water temperature as inputs to maintain the optimum tuning condition with sufficient accuracy. The newly acquired Dimtel iGp12 processor box is central to the HOM frequency measurements.

INTRODUCTION

Experience at the Advanced Photon Source (APS) storage ring has indicated that the monopole high-order mode (HOM) frequencies of the sixteen 352-MHz accelerating rf cavities, rather than drifting randomly with time by unknown causes, actually follow a reproducible function of cavity temperature. The temperature of a cavity, in turn, depends on two primary operational parameters, namely cooling water temperature and power absorbed into the cavity wall, both of which are well controlled. This leads to the idea mentioned in [1] that if the frequencies of the relevant HOMs and their dependence on temperature are determined precisely enough, then the multi-bunch stability of the beam in the APS Upgrade (APS-U) ring can be assessed immediately. This is particularly important because the new rf frequency of APS-U will be 110 kHz higher than in APS, changing the set of problematic HOMs. Cavity temperature settings that optimize HOM placement, which we call "smart" tuning, can be known in advance of the APS-U beam commissioning. Even though a longitudinal feedback system will cure multi-bunch instabilities, any mitigation of instability growth rate will help.

This paper will present the HOMs that have been characterized so far, and the thermal model of the HOM frequency change.

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First we review the motivation for temperature tuning the cavities. Figure 1 show the spectrum of the APS cavity monopole HOMs from an URMEL model along with curves comparing the longitudinal instability thresholds for APS and APS-U. The thresholds are calculated from the simple formula of longitudinal growth rate assuming one HOM in resonance. There are a total of 96 HOMs from different cavities, some of which will certainly overlap to produce higher growth rates when cavity temperatures have no particular setting. For the APS-U an additional assumption is that the high-harmonic cavity (HHC) is off. With HHC turned on the growth increases by factor 2-3 and the threshold will drop proportionately, a worsening of the situation.

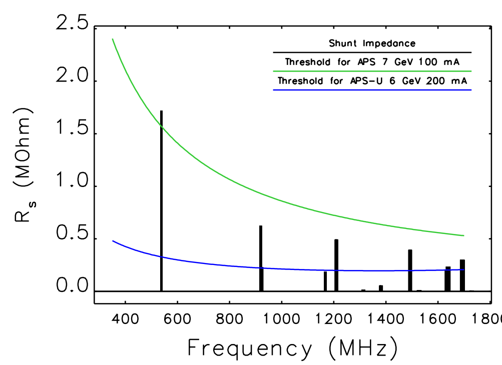

Figure 1: Thresholds of longitudinal instability for APS and APS-U.

MODELING OF HOM FREQUENCY

Each of the APS cavities have slightly different dimensions of its central body segment for the purpose of spreading the HOM frequencies. The spread varies with the particular HOM family and is typically 10 MHz. These HOM frequencies can be measured from cavity antenna probes with a spectrum analyzer reading revolution harmonic lines from a single-bunch stored beam. The resolution is only 271 kHz resolution, but is useful information when combined with beam mode detection with the iGp12 mentioned later, resulting in a very good picture of the HOM spectrum.

The frequency of the HOM proved to be very reproducible with temperature. The cavity temperatures correlated with just two other physical parameters, the cooling water circuit and the cavity power probe signal.

Reference [1] puts forth a thermal model of HOM frequency that change with cavity temperature along with a

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linear coefficient to be fitted. The simplest physical model is a cavity that expands isotropically with temperature with HOM frequencies following $f = f_{\mathrm{ref}}(1 - \alpha_{Cu}(T - T_{\mathrm{ref}}))$ where α_{Cu} is the expansion coefficient of copper, and T_{ref} and f_{ref} are reference cavity temperatures and HOM frequency values. We find that using $\alpha_{Cu} = 9.4 \times 10^{-6}$ as model coefficient agrees well with measurements of the two 1200 MHz HOMs that were tracked in a 24 deg F change. Reference [1] presents a coefficient for 537 MHz HOMs measured by other means that agrees with α_{Cu} as well, but with a larger uncertainty.

To give another practical illustration of cavity expansion, a 1-deg F change on a 1 GHz HOM gives a 10 kHz frequency change, which is a few times less than a typical resonator impedance width. Thus a 1 deg F change can bring a HOM into or out of a resonance, which has been APS's experience. This observation indicates that an accuracy of ~ 10 kHz for the measuring the HOM frequency is possible.

At APS we have temperature readbacks on three locations on the cavity body (besides the 15 or so for the flanges, tuner, and coupler). They change in agreement with the water temperature setting as expected. The difficulty comes with the observed individual dependence on cavity power dissipation. As the cavity wall power changes the temperatures of the various parts of the cavity will change at a slightly different rate. This could be for various physical reasons, say, water flow difference between parallel channels. Averaging the readings of one cavity is an option for parameterizing the cavity.

An alternative formulation is to replace cavity temperature readback with a model of the temperature increase due to cavity wall power P_c plus the cooling water temperature T_w. The cavity wall power may be a more consistent measurement than the cavity temperature readbacks. Furthermore, the pair T_w and P_c are more or less set by operational requirements. The cooling water temperature is a direct set point for cooling circuits, while the cavity wall power is determined by the gap voltage requirement in user beam operation. In APS-U the total gap voltage could be expected to be adjusted continually as undulator gaps are opened and closed.

The resulting relative cavity temperature is thus $(T - T_{\mathrm{ref}}) = T_w - T_{w,\mathrm{ref}} + B(P_c - P_{c,\mathrm{ref}})$ where coefficient $B = dT/dP_c$ is determined empirically for each cavities. For simplicity we assume this B coefficient is the same for all cavities. For APS cavities the coefficient is determined from measured cavity body temperature dependence on measured cavity power and is about 0.25 deg F/kW (i.e., Figure 2), confirmed by an incidental in-tunnel IR camera measurement. Note that the presence of beam could affect the heat deposited and the temperature, which will not be seen by the fundamental power probe, as it measured only the power in the fundamental mode.

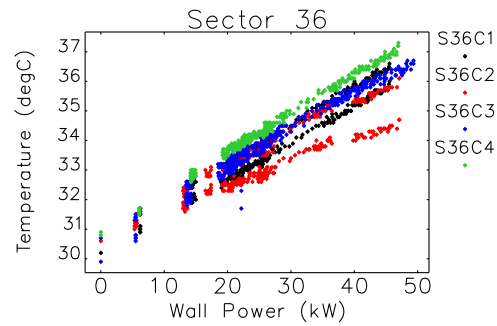

Figure 2: Temperature probe versus cavity wall power for sector 36 cavities. Two probes per cavity are shown. Data shows a linear dependence, which is not surprising.

EXPERIMENTAL METHOD

The experimental method of characterizing HOM is described in reference [1, and references therein]. Briefly, the excite-damp measurement of the Dimtel iGP12 consists of periodically interrupting an otherwise continuous excitation of a selected beam mode to allow the beam to damp naturally for a short period, say, 35 ms. During this short damping period a bunch-by-bunch signal is acquired and post-processed with a numerical algorithm provided by Dimtel, which produces a damping rate and a synchrotron frequency of the targeted beam mode, both of which relate to the aliased impedances that the targeted beam mode sees.

At APS the iGp12 works in the longitudinal plane, applying an energy modulation on the multi-bunch beam while driving transverse striplines in common mode with the aid of 500 W AR 500A250B amplifiers (APS doesn't have a longitudinal kicker). The beam signal acquired by the iGp12 is the bunch-by-bunch phase signal from a raw button sum signal passed through a phase detector. During excitation the bpm sum signal strength is about 0.01 degree with the 7 GeV beam, strong enough for analysis. At 6 GeV, the synchrotron radiation damping is about 40% less and the signal strength is doubled.

Through various MATLAB scripts and EPICS control system the iGp12 is made to scan a list of beam modes every 0.5 seconds. To reduce the uncertainty on the damping rate measurement, the iGp12 is made to repeat acquisition for each beam mode several times, say 4 to 6 times.

Typically we fill 324 bunches, that is, every fourth rf bucket for the 352-MHz, 1296-bucket machine. This allows us to scan 323 modes (skipping mode 0) and 323 possible locations for HOM impedances aliased into a 88 MHz band. The results is a list of decay rates for each beam mode index. Each decay rate value is the sum of the synchrotron radiation damping (a constant) and the growth (or decay) rate due to the aliased HOM impedance at the frequency of the beam mode. The peaks of decay rate represent the impedance of one HOM usually. Since the HOM impedance are narrow, say 10 kHz in width, most HOMs are not seen by the beam. We must scan the cavity cooling water temperatures over

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Table 1: Temperatures at which a HOM become resonant with 1 deg F steps. The HOM's closest beam mode for a 324 bunch pattern is denoted in cells.

Sectors	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
Mode #																													
S36C1											141			168			236												
S36C2																	136			30		226							
S36C3				247													146											246	
S36C4		243										36							144							242			
S37C1											263																43		
S37C2										261														153					
S37C3	252																									39	251		
S37C4																							44	265					
S40C1											238																		
S40C2										241																			
S40C3								232											32										
S40C4														229							31								
S40C4														303															

537 MHz HOM family · 921 MHz HOM family · 1498 MHz HOM family · 1205 MHz HOM family · 935 MHz HOM family

a wide range (72 deg F to 100 deg F) to make the HOMs resonant at some temperature and thus measurable at the fixed set of beam frequencies.

In APS four cavities of one sector share one cooling water circuit. Thus the HOMs of four cavities will be detected together. However spectrum analyzer data acquired earlier with a single bunch beam gives us an idea of which cavity HOM is associated to a particular beam mode.

RESULTS

Over several beam studies shift, we have determined the temperatures at which several HOMs in each cavity have a peak response. We used a beam with 324 equally-spaced and equally-filled bunches for the majority of the measurements, thus the HOMs were determined within a band of 88 MHz. Table 1 displays each HOM found for each cavity along with a beam mode number, skipping sector 38, which will not be part of APS-U. The cavities were set to the usual 9.5 MV total gap voltage. Presumably if the gap voltage were to change, then the temperature axis would effectively shift according the $B = 0.25$ deg F/kW coefficient. A cavity wall power change of, say, -12 kW in each cavity (for a 7.5 MV total gap voltage), would shift the temperature values of all HOMs by +3 deg F, a significant amount.

Measurements of HOMs higher than 1200 MHz have proved difficult. To quickly asses the situation we have made damping rate measurements on 648 bunches with changing the temperature of all cavity sectors together. The clusters in peaks of the growth rate from the 16 cavities over a large temperature range gives the strength of the HOM family. Figure 3 shows the overlay of growth rates of temperatures 75 deg F to 85 deg F. We verify that the 1500 MHz HOMs, known to drive modes in the region of 300 are truly damped strongly for some reason. The HOM families for 537, 921, 935 and 1205 MHz are seen at the expected mode numbers. The other HOM families shown in Figure 1 are frankly not visible.

We have not yet completed the full temperature scans on the three sectors of relevance for APS-U. We only found about 75 % of the HOMs from the four strongest families.

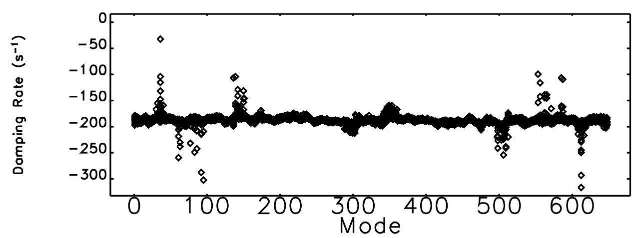

Figure 3: Overlay of growth rates for 75 deg F to 85 deg F in 1 deg F steps. Measured at about 75 mA.

Inspection of Table 1 gives the reader already a good idea of how to temperature-tune each cavity or cavity sectors. As long as there is a margin of 1 or 2 deg F from the occurrence of HOM resonance, there should be stability.

Another application of the HOM data collected would be to produce in real-time (using EPICS) the expected closeness of instability from any of the visible HOMs at APS or at APS-U. One merely has to acquire the temperature of the water cooling temperature and the probe signal for each cavity j, and use the formula $f_{i,j} = f_{i,j,\mathrm{ref}}(1 - \alpha(T_{w,j} - T_{w,\mathrm{ref}} + B(P_{c,j} - P_{c,\mathrm{ref}}))$ for each HOM i of cavity j.

CONCLUSIONS

We have gathered a large data set of HOM resonance peaks over wide cavity temperature ranges, from which we can determine accurate resonance frequencies at nominal temperature and cavity power conditions. A solution for optimum cavity temperatures tuning is rendered feasible for future operation of APS-U despite a change in working rf frequency and cavity power.

ACKNOWLEDGMENTS

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