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DESIGN PROGRESS OF ALS-U 3rd-HARMONIC CAVITY

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Abstract

A higher-harmonic rf cavity (HHC) system is required in the ALS-U storage ring to lengthen the bunches, reduce intrabeam-scattering effects, and improve Touschek beam lifetime. A 3rd harmonic, normal conducting, passive-cavity system has been chosen based on beam-dynamics requirements and cost considerations. We have explored two options for ALS-U 3HC system: a high-R/Q re-entrant cavity with waveguide HOM dampers, and a low-R/Q system with two elliptical cavities and HOM beam line absorbers. In this paper, we present the recent progress on the cavity design and related beam dynamics studies.

INTRODUCTION

The ALS-U project is the upgrade of the present LBNL Advanced Light Source (ALS) to a high-brightness soft X-ray diffraction-limited light source [1]. The high brightness comes at the expense of large scattering-effects in the electron beam. To mitigate these effects and, in particular, meet the Touschek beam-lifetime goal, the storage ring will include a higher-harmonic RF cavity system to lengthen the bunches by a factor 4 or more (the natural bunch length is about $\sigma_{z0} \simeq 3.9$ mm). Based on voltage requirement, cost, available space, and ease-of-operation considerations, a 3rd harmonic, normal-conducting, passive cavity system has been chosen.

A 3rd-harmonic system consisting of three identical cavities is already in use in the ALS. Unfortunately, while a single one of these cavities could serve the ALS-U needs, it would be inadequate to handle the heating caused by the beam dissipated power. Re-using two of the ALS cavities would solve the heating problem but the large combined shunt-impedance would not be well matched to the voltage requirement; it would force a tuning of the cavity too close to the $3\omega_{RF} + \omega_0$ frequency line causing a fast longitudinal coupled-bunch mode $\ell = 1$ instability [2]. As a result, the ALS-U 3HC will be a newly designed and built system.

RF DESIGN REQUIREMENTS AND BEAM-DYNAMICS CONSIDERATIONS

The ALS-U storage ring will re-utilize the two ALS 500 MHz main rf cavities, with a total-voltage requirement of about $V_{RF} = 0.6$ MV (close to half the ALS voltage). This drives the voltage requirement for the higher-harmonic cavity system, in first rough approximation equal to $V_{HC} \simeq V_{RF}/n$, where n is the higher-harmonic number. As noted in the introduction, a single $R \sim 2\,\text{M}\Omega$ and $R/Q \sim 80\,\Omega$ cavity similar to those already installed in the ALS would be sufficient to achieve the modest $V_{HC} \sim 0.2$ MV required from a passive $n = 3$ system with a 500 mA average beam current. Assuming a uniform-fill beam, the desired factor-4 bunch lengthening can nominally be obtained by detuning the cavity resonance about 300 kHz off the third harmonic ($3\omega_{RF}$). However, the ALS-U beam fill is not uniform, consisting of 11 bunch-trains separated by 10 ns gaps. The gaps have two consequences: they introduce a bunch-to-bunch variation in lengthening (transient beam loading) and force the tuning of the cavity closer to the third harmonic in order to approach, on average, the desired factor-4 bunch lengthening. In turn, the latter causes "overstretching", that is some of the bunches start to develop a double-hump profile. Macroparticle simulations show that under these conditions an apparently uncontrollable instability sets in.

In consideration of these results, we have explored an alternate design with a much reduced $R/Q \sim 40\ \Omega$ and (total) $R \sim 1.5\ \text{M}\Omega$ shunt impedance. This design has the drawback of requiring two cavities but macroparticle simulations show that stable operation with detuning yielding an average factor-4 bunch lengthening is possible. Moreover, because beam-loading transients scale with R/Q, bunch-to-bunch variations in this second design are notably reduced. Finally, and perhaps most significantly, the lower R/Q design appears to be compatible with overstretching the bunches to about a factor-5 lengthening (on average), which is close to optimum for lifetime. When overstretching in the presence of the $R/Q \sim 40\ \Omega$ 3HC, macroparticle simulations still show an instability but the instability is now different in nature and it appears controllable with a conventional bunch-to-bunch longitudinal feed-back system.

In the following we discuss the RF design for both high and low R/Q specifications.

RF DESIGN OF A R/Q=80 Ω 3HC SYSTEM

For the 3HC system with R/Q=80 Ω, we adopt the nosecone cavity profile similar to ALS 3HC and improve the cooling capability to achieve the required voltage with one cavity.

The 2D nosecone profile is optimized by multi-objective genetic algorithm (MOGA) [3], with the goals of minimizing the RF power while maximizing the quality factor Q.

The 3D design is shown in Fig. 1. The higher order modes (HOM) are damped through three dumbbell-shape waveguides, 120 degree apart from each other to damp both horizonal and vertical modes. They are placed on one side of the cavity to break the symmetry to damp the longitudinal

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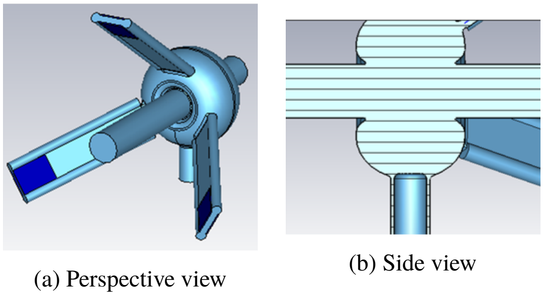


(a) Perspective view (b) Side view

Figure 1: High R/Q cavity design.

dipole modes. Lossy ferrites are placed at the end of the waveguides to absorb HOM power.

The cavity frequency is tuned by a piston tuner, the same way as ALS 3HC. The piston dimensions are designed to provide enough tuning sensitivity while not degrading the cavity quality factor too much.

The cavity fundamental mode properties are listed in Table 1. The beam dynamics requirements are satisfied and the target bunch lengthening can be achieved with just one cavity. The peak power density at the damping waveguide coupling slots is high, but should still be manageable with careful local cooling design.

Table 1: High R/Q Design Fundamental Mode RF Parameters

Frequency f (GHz)	1.506
R/Q (Ω)	81
Quality factor Q	24720
Shunt impedance R (MΩ)	2.0
Total power P (kW)	9.0 (@90% Q)
Peak surface E field E_{peak} (MV/m)	2.0
Peak power density PD_{peak} (W/cm^2)	60.0

[1] In this paper R is defined as $R = V^2/(2P)$.
[2] Power and fields are normalized to V=180 V.

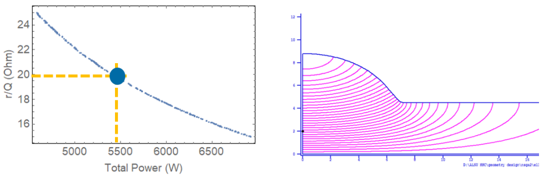
The HOM growth rates are calculated with analytical formulas. The strongest longitudinal HOM is damped to well below the radiation damping level. The transverse HOMs could be slightly higher than the radiation damping level but still well within the capability of the conventional transverse feedback system.

RF DESIGN OF A R/Q=40 Ω 3HC SYSTEM

For such low R/Q value, it requires two cavities to achieve the target voltage. We will present one cavity design with R/Q=20 Ω first, then look into the complete two-cavity system.

Design of One Cavity Unit with R/Q= 20 Ω

For a low R/Q value, we choose the elliptical shape and make the cavity long. The beampipe radius is chosen to be 45 mm, a compromise between the shunt impedance and the HOM damping. The 2D profile is optimized with MOGA. The objectives are set as minimizing the total power while maximizing the quality factor. From a well converged Pareto front, we chose the final 2D design whose R/Q=20 Ω, as shown in Fig. 2. Its fundamental mode RF performance, as listed in Table 2, satisfies the beam dynamics requirements.



(a) Converged Pareto front (b) Final 2D design

Figure 2: Cavity 2D profile design with MOGA.

Table 2: R/Q=20 Ω 2D Design RF Parameters

Frequency f (GHz)	1.506
Quality factor Q	37468
Shunt impedance R (MΩ)	0.74
Total power P (kW)	5.4
Peak surface E field E_{peak} (MV/m)	1.6
Peak power density PD_{peak} (W/cm^2)	8.9

Power and fields are normalized to V=90 V.

In order to damp the major longitudinal HOM TM011, the beampipe on one side is enlarged from 45 mm to 55 mm to let the TM011 propagate out. The damping is very effective, as shown in Fig. 3.

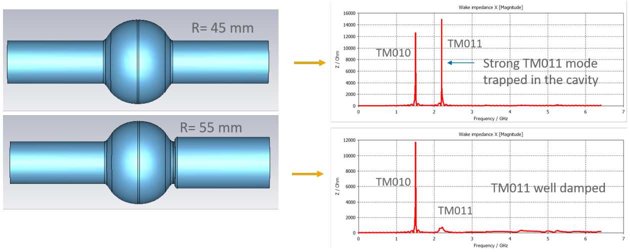


Figure 3: The damping of TM011 mode by the enlarged beampipe.

Another mode with a significant impedance if left undamped is the TE111 transverse mode at 1.44 GHz. This frequency is even lower than the TM010 mode. Comparing their EM field, as shown in Fig. 4, we can see although both modes are trapped in the cavity, the TE111 mode has a longer decay length into the beampipe. By putting a beam line absorber (BLA) at a proper location, we can damp the TE111 mode without affecting the TM010 mode.

The lossy materials for the BLA can be either magnetically lossy, such as ferrite, or electrically lossy, such as SiC. For both types of materials, we simulated the total quality factor Q_t for TM010 and TE111 mode with a varying BLA location. As the BLA moves closer to the cavity, the Q_t of both modes decrease, indicating a stronger power absorption.

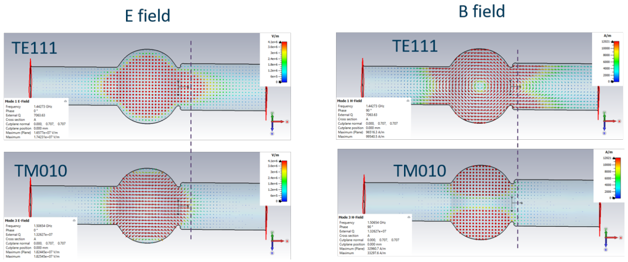
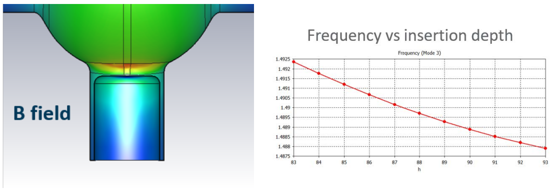


Figure 4: The field distribution of E and B field of TM010 and TE111 mode.

With a BLA made of SiC, the Q_t_TM011 drops from 37000 to 33000, while Q_t_TE111 is still around 5000. With a BLA made of ferrite, the Q_t_TM011 can be still at 35000 while Q_t_TE111 is already damped to 900. The better damping performance of ferrite BLA can be explained by the field distribution of E and B field. From Fig. 4 we can see the B fields of these two modes have a larger separation in the beam pipe than the E fields. Thus the magnetically-lossy BLA will have more distinct damping effects on these two modes. Thus we will use the lossy ferrite for our BLA instead of SiC. Notice that in this simulation, the ferrite lossy dispersion curve is fitted from the ferrite C48 data [4]. The difference between the real ferrite properties and the fitted data could change the final BLA location, but will not compromise the overall damping performance.

The same as the high R/Q design and the ALS cavities, the frequency will be tuned with a piston tuner, as shown in Fig. 5. Like ALS main cavity, the tuner length will be adjusted to prevent cavity modes from coupling into the tuner, and the problematic sliding RF seal will not be used.



(a) Piston tuner configuration

(b) Tuning sensitivity

Figure 5: Piston tuner for frequency tuning.

The multipacting is examined by both Track3P [5] and CST [6] PIC solver. Both simulations show negligible multipacting from almost zero to the operation power level.

Design of the Complete Two-cavity System

The complete two-cavity 3HC system is shown in Fig. 6. The distance between the two cavities is set at 400 mm, long enough to prevent the coupling of the TM010 mode between the cavities. Including the 10:1 ratio tapering on both sides from r=55 mm to 35 mm, the total length of the system is 1.34 m, sufficiently short to fit into the available space in the ALS-U RF straight section.

There are three ferrite BLAs, two on each side with a radius of 55 mm and one in the middle with a radius of 45 mm.

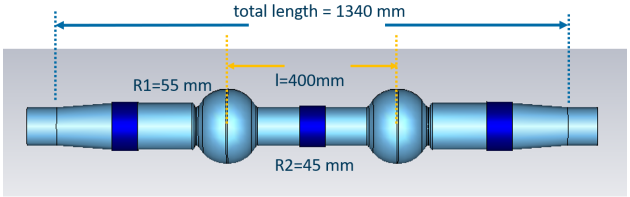


Figure 6: The complete 2-cavity 3HC system, piston tuners not included.

The impedance spectrums of the complete 3HC system is calculated by CST wakefield solver. The maximum longitudinal HOM is the TM011 at 2.158 GHz, with Z=3 kΩ and Q=178. The maxium transverse mode is the TE111 at 1.443 GHz, with Z=174 kΩ/m and Q=830. The corresponding growth rates are both below radiation damping.

CONCLUSION

We have discussed two proposed RF designs for the ALS-U 3HC system, with total R/Q of about 80 Ω and 40 Ω. Both meet specifications but beam dynamics studies favor the lower R/Q solution, which is associated with more stable beahavior and smaller beam-loading transients, and can enable bunch lengthening up to a factor 5. We have shown that with appropriate choice of ferrite loads, the offensive HOMs can be effectively damped without affecting the fundamental TM010 mode.

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