

# DESIGN STUDY OF THE HIGHER HARMONIC CAVITY FOR ADVANCED PHOTON SOURCE UPGRADE\*

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## Abstract

A higher-harmonic cavity is planned for the proposed Advanced Photon Source (APS) multi-bend achromat (MBA) lattice to increase the bunch length, improve the Touschek lifetime and increase the single-bunch current limit. We have investigated a range of options including 3rd, 4th, and 5th harmonics of the main radio frequency (RF) system, as well as configurations with and without external RF power couplers. The current baseline is a single 4th harmonic superconducting cavity with adjustable RF couplers and a slow tuner which provide the flexibility to operate over a wide range of beam currents. The cavity is designed to provide 0.84 MV at 1408 MHz for the nominal 6 GeV, 200 mA electron beam, and 4.1 MV main RF voltage. In this paper, we discuss the harmonic cavity parameters based on analytical calculations of the equilibrium bunch distribution and make comparisons to other options.

## INTRODUCTION

The APS at Argonne National Laboratory is planning an upgrade based on a MBA lattice for which the transverse emittance will be much smaller [1,2]. Beam dynamics studies show very small transverse beam sizes, ~10 μm rms in both the horizontal and vertical directions, which will result in more frequent Touschek scattering. To reduce the Touschek scattering probability a higher harmonic bunch lengthening RF system will be required and in this paper we will present how this improves the Touschek lifetime [1,2].

Physics parameters for the higher-harmonic cavity (HHC) have been derived from this study. Possible options for the HHC were as follows:

- Harmonic number, for example, 3rd, 4th, or 5th.
- Superconducting or normal conducting.
- Passive (driven only by beam) or active mode (including an external RF generator).
- In passive mode, with or without external RF power couplers.

As a baseline design we have chosen a 4th harmonic superconducting cavity operated in the passive mode with external RF power couplers terminated in matched loads. This was done based on analytical calculations of the equilibrium longitudinal bunch distribution for the combined RF voltage of the main and higher harmonic system. A unique feature of this design compared to that of other machines, such as ALS and ELETTRA [3,4], will

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be the use of adjustable RF power couplers. In combination with a frequency tuner, this permits adjustment of both the amplitude and phase of the harmonic voltage such that the cavity can be optimized for different beam currents even in the passive mode of operation.

In the following section, we will discuss the ‘optimum’ bunch lengthening condition, the harmonic number, the choice for superconducting technology, and operation at different beam currents. Non-optimum conditions will also be discussed. The detailed design of the HHC is presented in [5] and particle tracking simulations with the HHC are discussed in the [6].

## HHC PARAMETERS

### Optimum Bunch-Lengthening Condition

The longitudinal charge distribution in a bunch was analytically calculated from the potential well generated by the main and harmonic RF voltage. The combined RF voltage  $V$  seen by an electron at phase  $\phi$  is represented by [3,7]

$$V(\phi) = V_m \{ \sin(\phi + \phi_m) + k \sin(n\phi + \phi_h) \}, \quad (1)$$

where  $V_m$  is the main RF voltage,  $k$  is the ratio of the harmonic voltage to the main RF voltage,  $n$  is the harmonic RF number,  $\phi_m$  is the phase of the main RF,  $\phi_h$  is the phase of the harmonic voltage. The charge distribution,  $\rho$ , in equilibrium with radiation damping and quantum excitation can be represented by [3,8]

$$\rho(\phi) = \rho_0 \exp\left(\frac{-\Phi(\phi)}{\alpha_c^2 \sigma_e^2}\right), \quad (2)$$

where  $\rho_0$  is a normalization factor,  $\alpha_c$  is the momentum compaction factor,  $\sigma_e$ : the relative RMS energy spread, and  $\Phi$  is the potential defined by [3,7]

$$\Phi(\phi) = \frac{\alpha_p}{2\pi h E_s} \int_0^\phi \{ eV(\phi') - U_0 \} d\phi', \quad (3)$$

where  $E_s$  is the synchronous energy,  $h$  is the harmonic number of the main RF relative to the ring revolution frequency, and  $U_0$  is the energy loss per turn. In this study, we use the following values:  $V_m = 4.1$  MV,  $U_0 = 2.24$  MeV,  $h = 1296$ ,  $\alpha_c = 5.86 \times 10^{-5}$ ,  $\sigma_e = 9.5 \times 10^{-4}$ .

The ‘optimum’ condition for bunch lengthening is to cancel the slope of the main RF at the bunch center such that the potential well is flat around the bunch center. Under this condition, the first and second derivatives of  $V(\phi)$  must vanish at the synchronous phase [3,7]. The

optimum condition determines a unique set of  $\phi_s, k, \phi_h$  for a given RF voltage  $V_m$  and harmonic number  $n$  in Eq. (1). For example, the ‘optimum’ condition with a 4th harmonic produces the voltage and symmetric bunch distribution shown in Fig. 1.

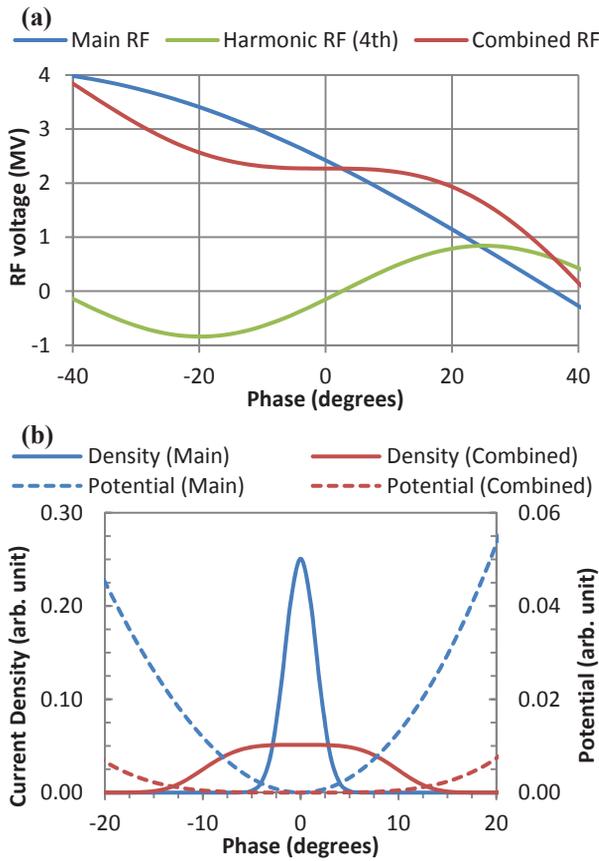


Figure 1: (a): RF voltages and (b): potential wells and bunch distributions for use of the main RF only and use of the main RF with the 4th harmonic at the ‘optimum’ condition.

### Harmonic Number

The harmonic RF voltages required for the ‘optimum’ condition are listed in Table 1 along with the nominal maximum Touschek lifetime improvement for three different harmonic numbers. The primary improvement in lifetime comes from the bunch length, since the momentum acceptance differences are relatively small. The bunch length is maximum for a 3rd harmonic, however, the beam loss power, which needs to be extracted out through RF power couplers, is substantially higher. For a 4th harmonic, on the other hand, even though the lengthening effect is ~20% lower than for a 3rd harmonic the beam loss power is moderate. Thus a 4th harmonic was chosen as the baseline. The ‘relative improvement of the Touschek lifetime’ in Table 1 is defined by [3]

$$\frac{\tau_{HHC}}{\tau_0} = \frac{\epsilon_{HHC}^2 \int \rho_0^2 d\phi}{\epsilon_0^2 \int \rho_{HHC}^2 d\phi} \quad (4)$$

where  $\tau$  is the Touschek lifetime,  $\epsilon$  is the RF acceptance, and both subscriptions, ‘HHC’ and ‘0’, respectively denote the cases with and without HHC. Clearly the calculated bunch length does not include broadening from other effects such as the short-term wake impedance [2].

Table 1: Comparison of HHC Parameters and Performances for Different Harmonic Numbers

	No HHC	3rd HHC	4th HHC	5th HHC
Synchronous phase relative to main RF (degrees)	146.9	142.1	144.4	145.3
Harmonic RF voltage, $kV_m$ (MV)	-	1.1	0.84	0.68
Harmonic RF phase, $n\phi_h$ (degrees)	-	-14.6	-10.2	-7.9
HHC detuning angle*, $\psi_h$ (degrees)	-	75.4	79.8	82.1
Beam loss power (kW)	-	52	27	17
RF acceptance (%)	4.1	4.0	3.9	3.8
RMS bunch length (ps)	12	59	50	44
Relative improvement of Touschek lifetime	1.0	4.8	3.8	3.2

\* $\psi_h = 90^\circ + n\phi_h$  at the ‘optimum’ condition

### Superconducting vs. Normal Conducting Cavity

Superconducting niobium cavities have a high intrinsic quality factor,  $Q_0 > 10^8$  at  $T = 4.5$  K, such that the harmonic voltage could be passively generated using a single cavity. A critical practical requirement is the necessity for the cavity and all subsystems to fit within half of an APS 5 m long straight section. The wall loss power is estimated to be ~30 W at  $Q_0 \sim 2 \times 10^8$  which is tolerable.

Room-temperature copper cavities have a significantly lower intrinsic quality factor, thus multiple cavities would be required. For example, referencing the ALS 1.5 GHz 3rd harmonic cavity, where the cavity  $R/Q = V_{sh}^2/P$  is 160 Ohms and  $Q_0$  is expected to be  $2.2 \times 10^4$  at 1.4 GHz [9], the wall loss power is expected to be ~5 kW per cavity when using 7 cavities. Copper cavity performance beyond the present state-of-the art for operational machines [9-11] might be achieved through R&D, reducing the requirement to 4 cavities. However, this would still be larger and more complex than a single SC cavity. Extraction of the beam loss power through RF power couplers may reduce the amount of wall loss power, but the lengthening would be far from optimum due to non-ideal phasing of the HHC voltage. This would be even without any RF power couplers. Furthermore, copper cavities require a smaller beam pipe diameter compared to SC cavities to achieve a high shunt impedance. Total higher-order mode (HOM) power and the difficulty of extracting it would be less favorable.

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## Operation at Different Beam Currents

The adjustable HHC parameters such as the detuning frequency and the external Q of the RF power couplers can be optimized for operation at different beam currents. Figure 2 shows these adjustable parameters at different beam currents between 50 and 200 mA such that the harmonic voltage and phase is always at the ‘optimum’ condition [5]. The dashed line in Fig. 2 indicates a threshold for Robinson’s instability excited by the HHC fundamental-mode impedance based on a macroparticle model [12]. The Robinson growth rate is positive on the left side of the threshold. However, the Robinson growth rate is smaller than the radiation damping rate for the beam currents,  $I_b \geq 100$  mA, lower than the threshold. Additionally Landau damping caused by the synchrotron frequency spread with HHC is expected to be beneficial [13]. Stability at lower beam currents is being studied by particle tracking simulations. Parameters for the main RF system are:  $R/Q = 109$  Ohm, loaded Q = 9110, detuning angle = -38.3 degrees, and number of cavities = 12.

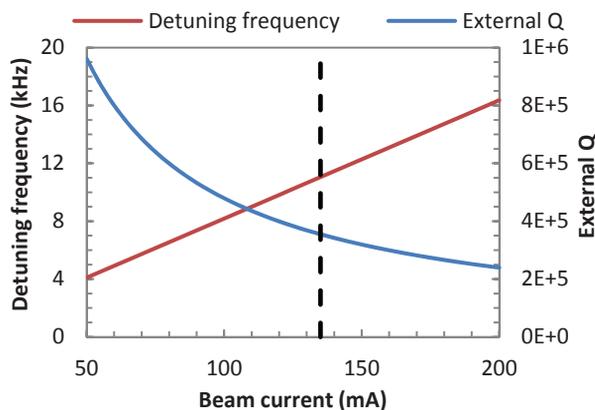


Figure 2: HHC parameters at different beam currents required for the optimum harmonic voltage and phase. Robinson growth rate based on the macroparticle model is positive on the left side of the dashed black line [12].

### Non-optimum Conditions

There are some interesting non-optimum conditions including: (1) using a higher harmonic voltage to lengthen the beam beyond the ‘optimum’ and (2) using a higher detuning angle to reduce the extracted RF power. Two examples are discussed:

- (i) Reducing the detuning frequency by 5% such that the harmonic voltage is  $\sim 5\%$  higher than the optimum,
- (ii) Retracting the RF power coupler to achieve a higher loaded Q and hence a larger required detuning angle for the same voltage amplitude. In this case, the harmonic RF phase seen at the bunch center is almost zero ( $\psi_h = 89.988^\circ$ ).

In case (i), the beam is over-stretched and partially separates into two due to the higher harmonic voltage as shown in Fig. 3. In case (ii), even though no RF power is extracted, the bunch shape is asymmetric as shown in Fig. 3. The bunch shape either in case (i) and (ii) is a self-consistent solution of Eqs. (1) and (2) for a given

detuning frequency and loaded Q of the HHC [14]. Detailed particle tracking simulations under non-optimum conditions have been performed in [6].

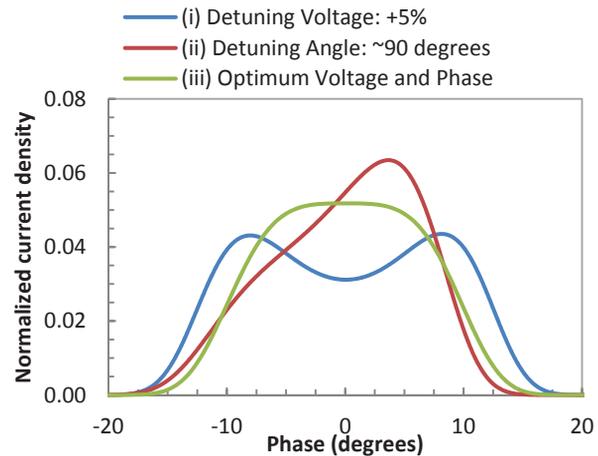


Figure 3: The bunch distributions for non-optimal HHC amplitude (i) and non-optimal phase (ii). The phase is referenced to the bunch center in each case.

## SUMMARY

A 4th harmonic superconducting cavity has been chosen as the baseline design for the bunch lengthening system in the APS upgrade. It can provide increased bunch length while keeping power handling requirements for the RF power couplers to a moderate level. It can also fit within a compact 2.5 meter envelope. This HHC will provide flexibility to operate over a wide range of beam currents using an adjustable RF power coupler and frequency tuner.

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