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SUPERCONDUCTING HARMONIC CAVITY FOR THE ADVANCED PHOTON SOURCE UPGRADE*

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Abstract

A new bunch lengthening cryomodule using a single-cell 'higher-harmonic' superconducting cavity (HHC) based on the TESLA shape and operating at the 4th harmonic (1408 MHz) of the main RF is under development at Argonne. The system will be used to improve the Touschek lifetime and increase the single-bunch current limit in the upgraded multibend achromat lattice of the Advanced Photon Source electron storage ring. The 4 K cryomodule will fit within one half of a straight section, ~2.5 meters, of the ring. The system will use a pair of moveable 20 kW (each) CW RF power couplers to adjust the loaded Q and extract power from the beam. This will provide the flexibility to adjust the impedance presented to the beam and run at various beam currents. Higher-order modes (HOMs) induced by the circulating electron beam will be extracted along the beam axis and damped using a pair of room temperature beam line absorbers. Engineering designs and the prototyping status for the cavity, power couplers and HOM absorbers are discussed.

INTRODUCTION

The Advanced Photon Source Upgrade (APS-U) project [1] will have a relatively short Touschek lifetime [2] and a bunch lengthening cavity is required to mitigate the effect. Harmonic cavities provide lengthening by modifying the longitudinal potential to produce reduced slope near the bunch center [3] and are demonstrated and in use elsewhere [4,5].

Superconducting RF (SRF) cavities have major advantages over normal conducting cavities in many high-current, high-power CW applications, including for the 6 GeV, 200 mA electron storage ring in the APS-U:

- One beam-driven single-cell harmonic cavity easily provides all of the required voltage
- The large beam aperture and single-cell minimize the total beam-induced HOM power and the complexity of HOM power extraction
- The high quality factor, $Q_0>10^8$, combined with a variable coupler, permit adjustment of the loaded quality factor, Q_L, for near-optimal lengthening for various beam currents

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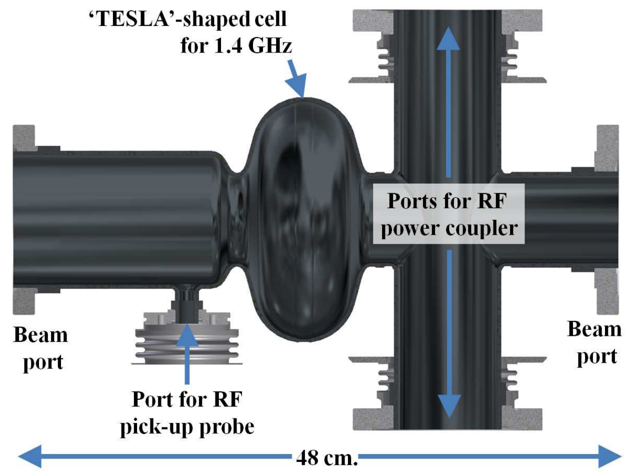

Figure 1: A higher-harmonic cavity for bunch lengthening in the Advanced Photon Source Upgrade.

A study of possible 3rd, 4th, and 5th harmonic SRF cavities has been performed based on analytical calculations. These assume 'optimal' bunch lengthening [6]. Differences are modest with the most lengthening, by ~20%, with the 3rd harmonic. However, the extracted power (through RF couplers) is double that for the 4th harmonic due to higher voltage and smaller detuning angle for the optimum condition. Multi-particle, collective effects and transients were not included. Tracking simulations [2] using ELEGANT, include these, and do not support a clear advantage with the 3rd harmonic. Finally, the 4th harmonic cavity choice (Figure 1) was influenced by practical considerations.

The 1.4 GHz frequency is sufficiently close to the 1.3 GHz linear collider frequency that existing infrastructure and techniques can be used to reduce development time. Performance needs are modest and are listed Table 1.

Table 1: Harmonic Cavity Main Parameters

Parameter	Value
Frequency, MHz	1408
Operating temperature, K	4.5
Beam induced voltage, MV	0.84
Cavity Q_0 at 4.5 K	2×10^8
R_{SH}/Q, Ω	109
G, Ω	270
E_{PEAK} at 0.9 MV, MV/m	16
B_{PEAK} at 0.9 MV, mT	33

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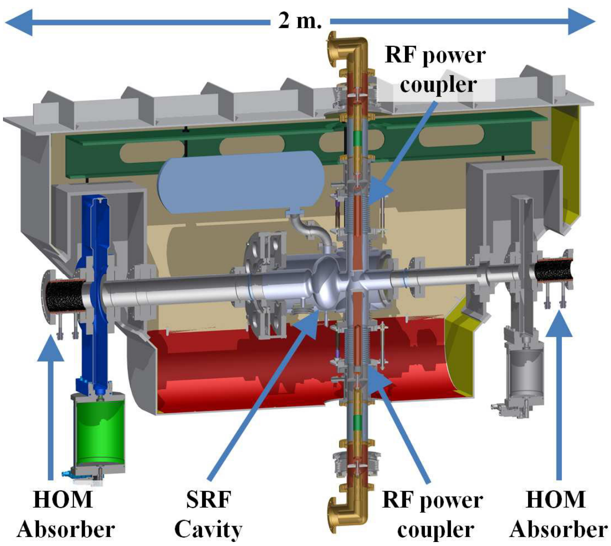

Figure 2: Conceptual design for a higher-harmonic cavity cryomodule.

A harmonic cavity system based on SRF technology requires that the cavity have an intrinsic quality factor, Q_0~10^8, in order that cavity wall losses and heat to the helium bath are manageable. High Q_0 of ~10^{10} is not needed and, therefore, the operating temperature is `relaxed' to 4.5 K. This avoids sub-atmospheric helium cryogenics and simplies cryomodule requirements. The main trade off is the additional vibrations that could be induced by boiling in the helium bath. However, with the low external, Q_{EXT}~6×10^5[2], the large loaded bandwidth of 2.3 kHz, and known techniques to mechanically stiffen a single-cell elliptical cavity, microphonics from helium boiling will not be an issue. The maximum CW beam loss power of 32 kW is extracted from the circulating 200 mA beam through a pair of fundamental power couplers (for minimum Q_{EXT}=2.4×10^5) located next to the cavity cell. The cavity will operate just above resonance with an offset frequency of approximately +15 kHz, as adjusted using a mechanical slow tuner. The offset frequency and Q_{EXT} uniquely determine the cavity RF voltage and phase with respect to the main RF.

Intrinsic properties of the cavity geometry including R_{SH}/Q and peak surface and electric fields are those for a cavity with the so-called TESLA shape developed in the early 1990's for the International Linear Collider. Harmonic cavity surface fields required here are modest by today's standards so the incentive to marginally improve through development a more 'advanced' shape is not strong.

R&D PLAN

The cavity and subsystems are based largely on demonstrated SRF technology, however, detailed designs are new. As such, R&D is underway to mitigate the risk of delay or costs of re-work, *e.g.* from cavity defects, coupler manufacturing or durability problems. Highest priority development is for:

- 1.4 GHz superconducting RF cavity
- A pair of 20 kW CW RF power couplers
- Higher-order mode dampers

Figure 2 shows a conceptual design for a cryomodule and these subsystems. A single SRF accelerating cavity will be cooled using 4.5 K liquid helium supplied from an external liquid helium refrigerator. RF power couplers are attached at two ports, oriented 180 degrees apart and vertically with respect to the beam axis. One cavity beam port opens to a larger, 10 cm diameter. This traps the fundamental (1.4 GHz, TM010) mode, but allows all other cavity monopole and dipole HOMs to pass down the 10 cm. beamline into a room temperature water-cooled HOM absorber. The smaller diameter HOM absorber (Fig. 2, right side) is required for damping electromagnetic modes excited within the beam pipe itself.

Cavity Design

An engineering study of the 1.4 GHz cavity has been completed. ANSYS was used to simulate cavity frequency sensitivities to cool down, axial tuning forces (see Figure 3), helium pressure fluctuations, as well as, material stresses, conditions for plastic collapse, buckling and mechanical Eigenmodes. The model uses the near-final niobium geometry assuming 3 mm niobium thickness and realistic thinning at the weld preparations. The He jacket is 3 mm stainless steel and most features are expected to be near final. Notably, a bellows (dashed box - Figure 3) is integrated into the helium vessel. The bellows diameter of 15 cm is smaller than the 23 cm diameter He vessel. This reduces the sensitivity to helium pressure, Δf/Δp, but gives sufficient compliance for slow

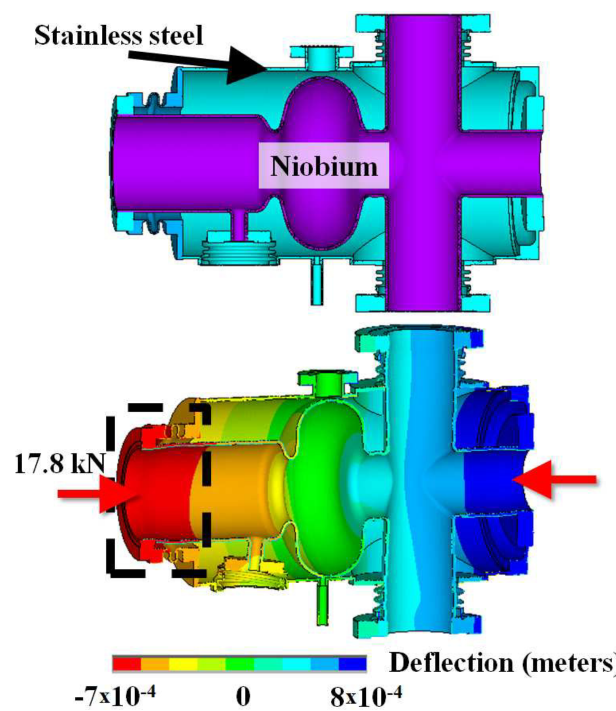

Figure 3: ANSYS mechanical model (top) and deflection (bottom) under a 17.8 kN axial tuner load. Δf=-540 kHz.

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tuning. A summary of simulated mechanical properties is listed in Table 2.

Table 2: Simulated Cavity Mechanical Parameters

Parameter	Value
Tuning sensitivity @ 4 K, Hz/N	-30
Tuning sensitivity @ 4 K, mm/kN	0.017
Tuning range, kHz	600
Max. Nb stress @ full tuner range, MPa	225
$\Delta f/\Delta p$, Hz/mbar	6.5
Δf (300 K-to-4 K), MHz	1.1
Threshold (ΔP) for Nb collapse, MPa	>0.4
Frequency 1st non-rigid body mode, Hz	>300

Fabrication of two 3 mm-thick, (RRR≈300) niobium cavities is underway. Forming, machining, electron beam welding and electropolishing will be similar to that used for recent ANL half-wave cavities [7].

RF Power Coupler and HOM Absorber

A pair of 4 cm movable fundamental RF couplers will extract power to maintain the 0.84 MV harmonic cavity voltage for a range of beam currents. The nominal maximum power is 32 kW (16 kW/coupler when $Q_{EXT}=2\times10^5$). 'Optimized' values [2] are expected to have lower extracted power and higher Q_{EXT}. Components for two couplers are being built and will be tested with a modified 20 kW CW RF amplifier at the slightly lower frequency of 1.3 GHz.

Each coupler will use two rugged disc-shaped alumina (WESGO Al300) windows, one each at room temperature and one cooled to 80 K. The central conductor will be 'hourglass'-shaped, as shown in Figure 4, to produce a 50

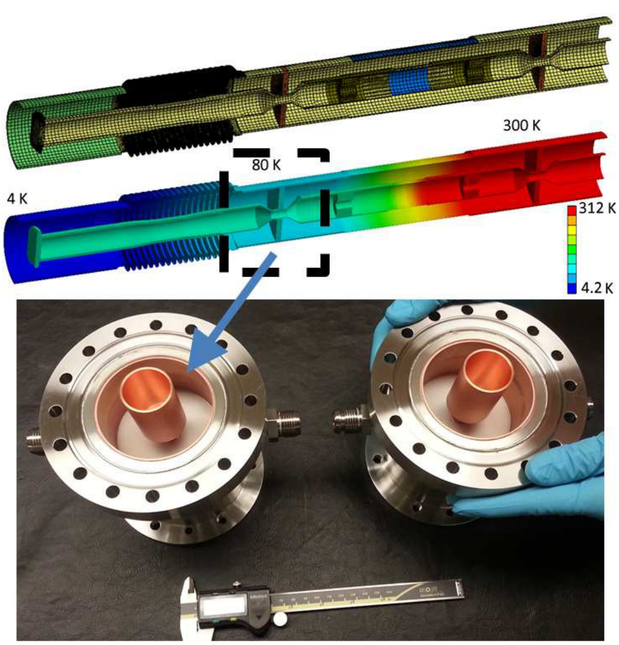

Figure 4: 20 kW capable RF power coupler for 1.4 GHz.

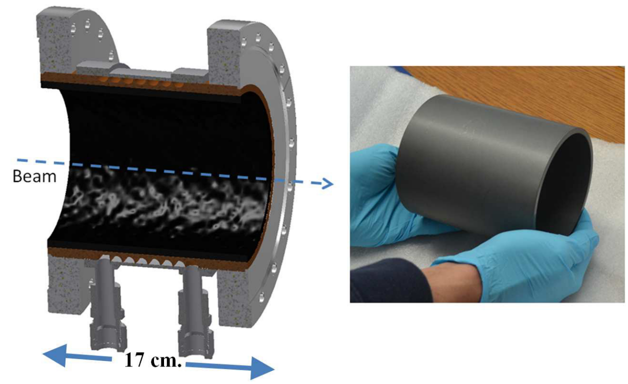

Figure 5: Room temperature beamline HOM absorber.

Ω match, optimized in simulations for 1.4 GHz.

HOM damping with room temperature silicon carbide (SiC) beamline absorbers, modelled in Fig. 5, looks promising based on extensive work elsewhere [8] and initial work at ANL. Our studies of Coorstek 35 material show good broadband losses, with $\tan\delta/\varepsilon\sim0.01$ for 2-3.5 GHz, and sufficiently high DC conductivity, $\sigma>10^{-4}$ S/m, to avoid electrical charging. The total HOM load is expected to be less than 2 kW.

SUMMARY

The conceptual design for a bunch lengthening cryomodule based on a single 1.4 GHz SC cavity is complete. Important systems including the SRF cavity, a pair of 20 kW CW capable power couplers and room temperature HOM absorbers are under development.

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