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SUPERCONDUCTING HARMONIC CAVITY FOR BUNCH LENGTHENING IN THE APS UPGRADE*

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Abstract

A superconducting cavity based Bunch Lengthening System is under construction for the Argonne's Advanced Photon Source (APS) Upgrade. The system will reduce the undesirable effects of Touschek scattering on the beam lifetime by providing bunch lengthening in the longitudinal direction by 2-4 times. The major technical components for the beam-driven 1.4 GHz fourth harmonic superconducting cryomodule are in hand and have been tested. These include a superconducting cavity, cw rf power couplers, a pneumatic cavity slow tuner and beamline higher-order mode absorbers. Initial assembly and engineering testing of the cryomodule is underway. Final integrated testing will be complete in 2021. Transportation to and commissioning in the APS is planned for 2022-23.

INTRODUCTION

The Argonne National Laboratory's Advanced Photon Source (APS) is entering the construction phase of a major upgrade of the synchrotron that involves replacement of the present storage ring with an ultra-low emittance design based on a multi-bend achromat. The small transverse beam size means that Touschek scattering will be the dominant effect on the storage ring beam lifetime.

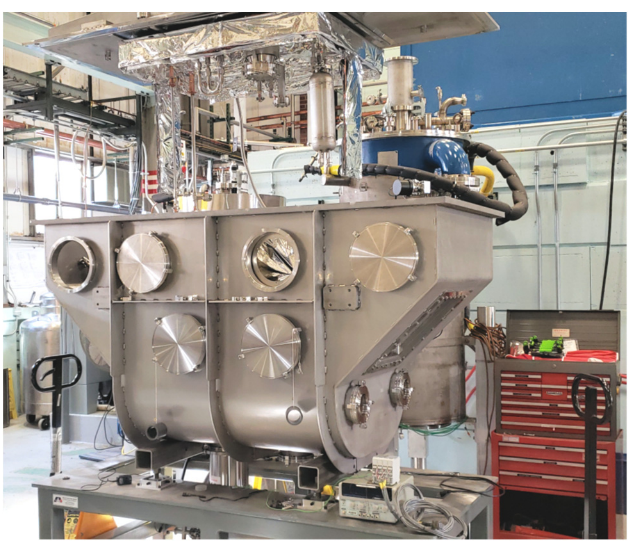

Figure 1: Top-loading 2-meter long bunch lengthening cryomodule.

Table 1: Bunch Lengthening System Parameters

Parameter	Value	Unit
Operating temperature	2.1	K
R/Q	104	Ohm
Quality factor (min. 2.1 K)	$6x10^9$	
External Q_L range	$2x10^5$-$2x10^7$	
Nominal Q_L	$6x10^5$	
Offset frequency	10	kHz
Cavity resonant frequency	1408	MHz
Beam induced voltage	1.25	MV
Detuning angle	83	degrees
Cavity loaded bandwidth	2.35	kHz
Beam loss power (Q_L=$6x10^5$)	25	kW
Cavity wall loss power	2.5	W
Peak surface E-field (@1.25 MV)	24	MV/m
Peak surface B-field	49	mT

To mitigate this effect, a single beam-driven 4th harmonic bunch lengthening cavity will be used to increase the rms bunch length to about 110 ps. The resulting beam lifetime will be about 3.5 hours for a 200 mA electron beam current distributed among 48 bunches [1].

Table 1 shows the basic design parameters which have evolved since the initial conception [2]. The cavity will operate at 2.1 K while providing an equivalent potential of 1.25 MV with reasonable losses into the liquid helium bath. The detuning angle of the rf field with respect to the time of arrival of the beam is 83 degrees (7 degrees from zero crossing) and is determined by the offset frequency, 10 kHz above resonance, and the nominal external quality factor of $6x10^5$. The nominal Q_L implies a beam loss power of 25 kW which will be extracted by two power couplers and dissipated into water-cooled loads outside of the cryomodule.

TECHNOLOGY DEVELOPMENT

4th Harmonic Cavity

A pair of 1.4 GHz niobium single-cell elliptical cavities have been fabricated, with one to be used for operations and the second as a production-ready spare. One cavity has been fully processed, assembled and tested in the ANL cavity test cryostat #2, while the second cavity will be tested in 2019-2020 inside of the recently delivered vacuum vessel shown in Figure 1.

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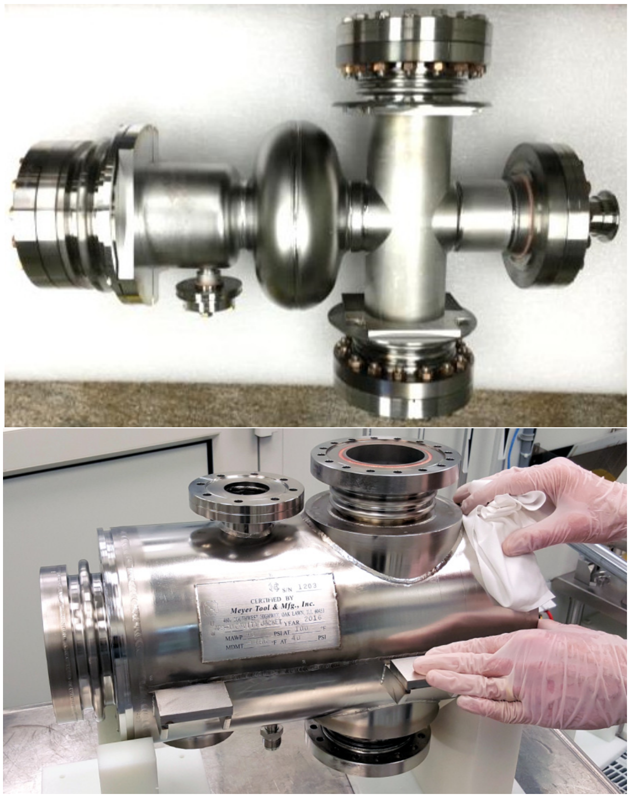

Figure 2: Niobium cavity subassembly (top) and production-ready higher-harmonic cavity (bottom).

The cavity beam ports (oriented roughly horizontally in Figure 2) are large diameter, 10 cm and 7 cm respectively, on left and right and naturally allow the important higher-order modes to 'flow' out of the cavity. The two large vertical ports oriented 180º apart are for the 20 kW nominal fundamental rf power couplers. A small rf pickup port is located on the cavity underside. The stainless steel helium vessel has two ports, one on the top and the other on the bottom, in order to facilitate cool down from room temperature at a rate of approximate 1 K/minute.

Figure 3 shows the measured cavity performance at 2 K and 4.5 K. The measured quality factor was close to the original design goal at 4.5 K and it exceeds the nominal design goal at 2 K. In the case of 4.5 K operation, the cavity fields were gradually turned up to an equivalent accelerating voltage of 1.1 MV over the course of several minutes. Interestingly, almost no conditioning activity was apparent as observed on the RF pickup signal or the test cryostat radiation monitoring system. The maximum voltage at 4.5 K was limited by the available 80 Watt 1.4 GHz RF amplifier.

For 2 K operation, the cavity field was turned up to 2.1 MV, also with no observable conditioning. However, at the maximum voltage, the onset of what is believed to be a multipacting barrier was observed as indicated by the presence of x-rays. During these tests, the explicit choice was made not to try to condition the barrier, since the voltage is nearly a factor of two above the nominal design value and aggressive conditioning is well-known to be a possible source of Q degradation.

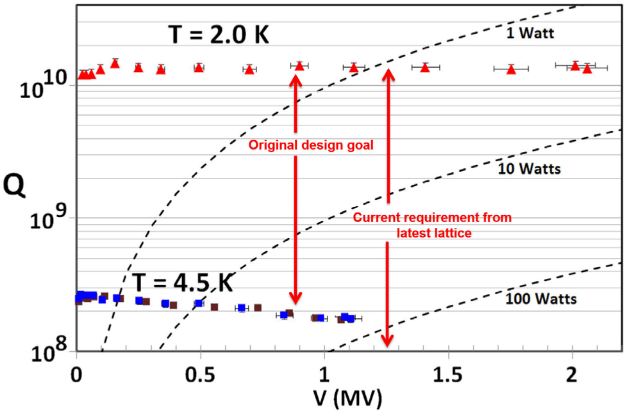

Figure 3: Cavity performance curves at 2 K at 4.5 K.

The cavity field performance at both 2 K or 4.5 K is, in principle suitable to provide V_{ACC} of about 1 MV with no further development. There are, however, important trade-offs between the two cases. Since the conception of the system in 2014, the requirements have evolved, and in particular due to additional energy losses in the storage ring insertion devices which were not initially considered. This led to a desire to increase the bunch lengthening voltage from 0.84 MV to 1.25 MV. At the higher voltage, the heat load at 4.5 K approaches 100 Watts so that 4.5 K operation becomes increasingly inefficient and less attractive. For this reason the choice was made to switch to nominal 2.1 K operation.

Higher-order Mode Absorbers

Cavity wakefields excited by the recirculating electron beam may be resonantly excited if the beam current spectrum drives one or more of the higher order modes (HOMs) in the harmonic cavity. These beam induced HOMs must be damped to avoid excessive cryogenic loads from RF heating and multi-bunch instabilities which could limit the practical single bunch charge. The strategy for HOM damping in the bunch lengthening system is to damp all possible monopole and dipole HOMs with the conservative assumption that they are excited on resonance by the beam. This strategy implies that we do not control the HOM resonant frequencies with respect to the beam harmonics.

Instead, a pair of broadband RF absorbers are positioned just outside the ends of the cryomodule at room temperature. These so-called beam pipe HOM absorbers are intended to damp all relevant HOMs. This method requires that HOMs excited in the cavity be extracted through beam pipes. One of the cavity beam pipes is flared to a diameter larger than the cavity iris such that the first and most strongly interacting HOM, the TE11 mode, propagates along the large 10 cm beam pipe. All other monopole and dipole modes propagate similarly out of one side or the other of the cavity, along the beam axis and into the water-cooled HOM absorbers.

The HOM absorber material is fundamentally a lossy ceramic hollow cylinder whose inner diameter is matched to the envelope of the beam pipe vacuum volume. The

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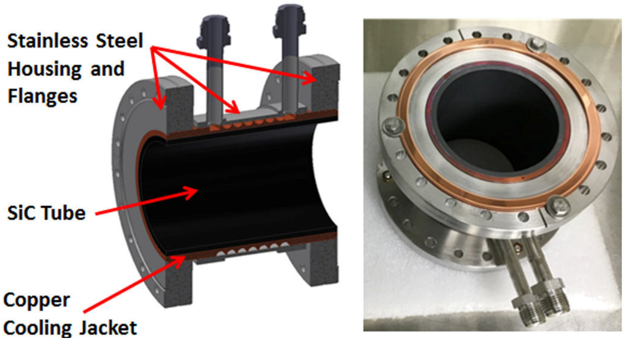

Figure 4: Higher order mode damper assembly.

graphite-direct-sintered silicon carbide, Coorstek SC-35, was been chosen based on experience in the Cornell ERL Injector Cryomodule [3]. Dielectric properties of this material, which determine the strength of HOM damping, have been experimentally characterized. Scattering parameters measured in a coaxial transmission line assembled with the SiC tube show that dielectric constant ε=45 and loss tangent, tanδ= 0.45.

The SiC tube inserted into the beam and visible in Figure 4 is itself a resonator with a broad bandwidth due to the high loss tangent. The inner diameters are 104 mm for the larger damper and 70 mm for the smaller and are the same as the cavity beam pipe inner diameters. The length and thickness are the same for both absorbers and are, 135 mm and 5 mm, respectively.

The dimensions of the SiC tubes, which determine the frequency range of the broadband resonance, were chosen such that the resonance of each SiC tube occurs for frequencies between 2 and 4 GHz. This is a favourable situation, since essentially all of the high R/Q modes for the harmonic cavity fall within this frequency range.

RF Power Couplers

The capability to adjust the loaded quality factor of the bunch lengthening system provides a valuable and independent means of optimizing the bunch lengthening properties. As such, a pair of fundamental rf power couplers was designed as part of the system. These will be used to extract up to 32 kW of rf power in order to maintain the 1.25 MV harmonic cavity voltage for a range of beam currents and to avoid the Robinson instability.

Each coupler will nominally extract half of the power and transport that power out of the cryomodule into a water cooled load. The coupler design is based on a pair of simple, rugged disc-shaped rf windows, one warm and one cold. The 50 Ω line impedance in the windows is maintained by tapering the center conductor, to a small diameter at the locations of the disk-shaped rf windows.

The components of the production coupler are shown in Figure 5 in the so-called test stand configuration where cw rf power was injected into one coupler, transmitted through a bridging section of coaxial line into the second coupler, and finally to a water-cooled load. The heating in the coupler was measured in full transmission using the available 18 kW of rf power at 1.3 GHz for 3 hours. Heating was measured using a series of thermometers

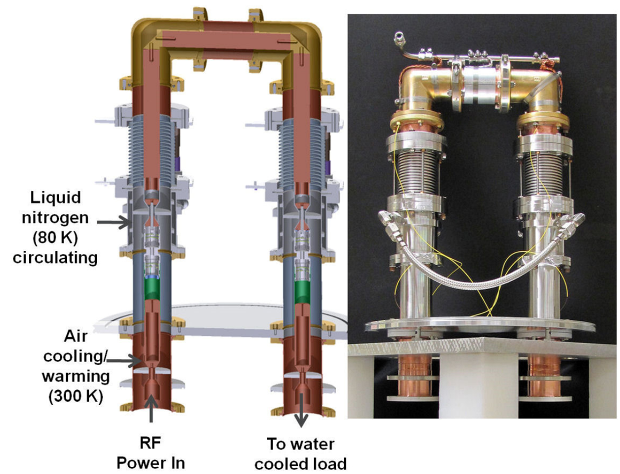

Figure 5: Test stand configuration for a pair of fundamental RF power couplers.

located both on the outside and inside of the transmission line. Similar measurements were performed for several lower levels of rf power with no problematic multipacting, conditioning, or excessive heating observed at any power level.

SU.MMARY

After successful development of the key technical components, a superconducting cavity-based Bunch Lengthening System is now under construction for the Argonne's Advanced Photon Source (APS) Upgrade. The system will provide a major practical benefit to the majority of APS users by increasing the storage ring beam lifetime by 2-4 times. The major technical components are the beam-driven 1.4 GHz fourth harmonic superconducting cavity, a simple and robust pair of beamline higher-order mode absorbers and a pair of 1.4 GHz cw rf power couplers. Initial assembly and engineering testing of the cryomodule is underway. Final integrated testing will be complete in 2021.

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