HORIZONTAL TESTING OF A DRESSED DEFLECTING MODE CAVITY FOR THE APS UPGRADE SHORT PULSE X-RAY PROJECT*

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Abstract

The short pulse x-ray (SPX) part of the Advanced Photon Source (APS) Upgrade is an effort to enhance time-resolved experiments on a few-ps scale at the APS. The goal of SPX is the generation of short pulses of x-rays for pump-probe time-resolved capability using superconducting rf (SRF) deflecting cavities. These cavities will create a correlation between longitudinal position in the electron bunch and vertical momentum. The light produced by this bunch can be passed through a slit to produce a pulse of light much shorter (1-2 ps instead of 100 ps) than the bunch length at reduced flux. An SPX cavity has been tested with a helium vessel and tuner as have the integration and operation of many systems designed for SPX cryomodule in-ring operation. These systems include an APS-constructed 5-kW, 2.815-GHz amplifier, a digital low-level rf controller system designed and fabricated in collaboration with LBNL, a cavity tuner, and instrumentation systems designed for the existing APS infrastructure. Cavity performance and subsystem performance will be reported and discussed in this paper.

INTRODUCTION

The SPX project calls for the use of an rf deflecting-mode cavity to chirp electron bunches, giving the electrons a correlation between their longitudinal position in the bunch and their vertical momentum. Synchrotron light produced from this bunch can then be passed through a physical slit to create a shorter light pulse at the proportional sacrifice of total flux. This scheme was first proposed by Zholents [1]; the scheme can be seen in Figure 1.

A significant amount of design work has gone into the rf cavities required for this project, details of which can be found in [2- 7]. This cavity application has many specific challenges including the need to heavily damp all non-operational modes to preserve beam quality for other APS users.

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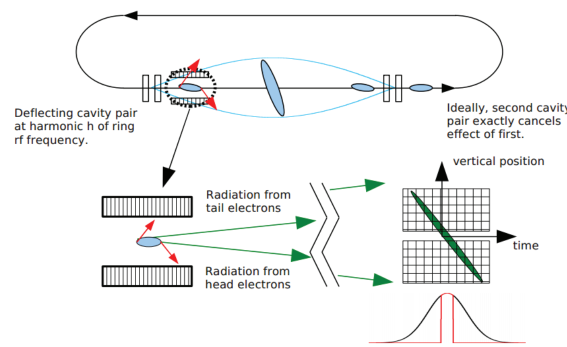

Figure 1: Schematic of Zholent's short pulse x-ray generation scheme. Image credit to [3].

CAVITY DESIGN

The current design is a squashed elliptical dipole-mode cavity with a Y-shaped end group and an on-cell damping port, which can all be seen in Figure 2. Two of the waveguides from the Y-end group will be used for damping of higher-order modes (HOMs) while the third will be primarily used as the forward power coupler. The on-cell damper is used primarily to damp the fundamental mode, called the lower-order mode (LOM).

Vertical Testing Results

The maximum expected reliable peak magnetic field is 120 mT with each cavity specified to operate at 0.5-MV deflecting voltage or 105 mT with a $Q_0 > 1E9$. Several rounds of testing and studies were required to reliably reach the specified field and quality factor. A more detailed description of this process and results can be seen in [8].

HORIZONTAL CAVITY TEST PLAN

In parallel with the progress being made on bare cavity testing, many of the subsystems needed for cryomodule operation were also under development. The horizontal cavity test (HCT) was planned to test may of these subsystems, including:

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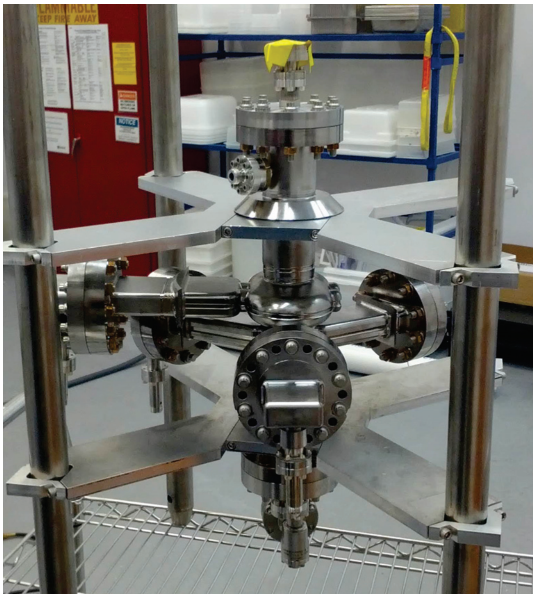

Figure 2: CCA3-1 prepared for vertical testing. The LOM waveguide can be seen on-cell pointing to the left and the Y-end group (HOM dampers and FPC) is below the cavity.

- Effects of helium vessel attachment to the cavity's SRF performance
- Tuner range, resolution, and drive system
- Digital low-level rf control system
- High-power rf amplifier performance

The dressed cavity on the test insert can be seen in Figure 3. The dressed cavity with tuner was hung from an intermediate plate that in turn connected to the helium reservoir. Helium was fed through a central stem with the forward power coupler (FPC) and warm tuner interfacing through the bottom of the cryostat.

With the insert secured into the cryostat and the bottom flange closed, the cryostat was turbo-pumped to provide insulating vacuum. Liquid nitrogen was used to cool an 80 K shield inside the cryostat as well as a thermal intercept on the FPC waveguide and tuner stack. A detailed description of the cryostat used can be found in [9]. All cavity ports beside the FPC and LOM were blanked and thermally braided to the 2 K circuit. The LOM waveguide and field probe rf connections were made through the cryostat lid.

Liquid helium was fed from either the ATLAS cryoplant [10] or 500 L Dewars. 2 K operation was provided by a 2.5-g/sec vacuum pump. Active cavity vacuum pumping was provided by a pump cart connected to the FPC waveguide, maintaining cavity pressure below $1E-7$ Torr.

CAVITY PERFORMANCE

Using the digital LLRF system, the loaded Q was measured at $9.23E5$, which agrees nicely with the desired value

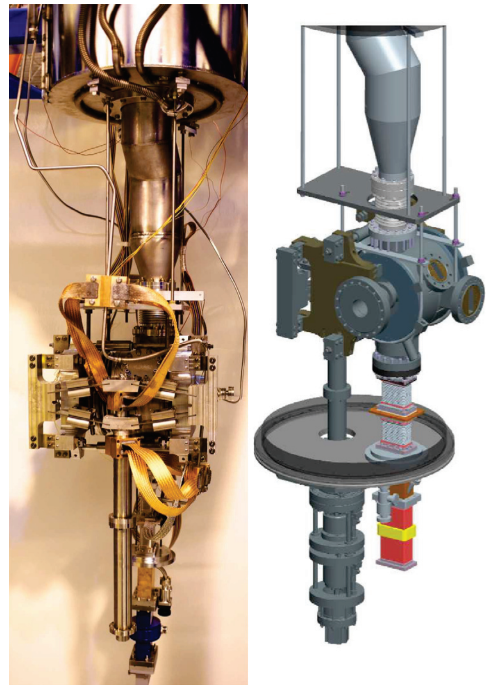

Figure 3: CCA3-1 hanging from the HCT cryo-insert. On the left, the tuner assembly can be seen in the foreground, mounted to the cavity. On the right, the cavity model shows the bottom flange that seals the bottom of the test cryostat mounted to the FPC waveguide and warm tuner stack.

of $1E6$. Dynamic measurements done with a fast oscilloscope give a field probe $Q_{ext} = 1.17E10$ and an LOM field probe $Q_{ext,2} = 2.52E10$, consistent with measurements performed on a warm cavity.

High-power measurements showed a stable maximum field of 76 mT. The limiting mechanism is believed to be heating in the LOM waveguide. This is supported by sharp jumps in measured temperature on the LOM waveguide flange at the moment of cavity field breakdown. This field level is consistent with the maximum field measured in this cavity during vertical testing. Pulsed measurements achieved 79 mT with a small duty cycle. Endurance tests of almost an hour failed to reveal any long-term thermal instabilities.

Calorimetric Q measurements were performed, but were unable to provide adequate measurement accuracy. It was discovered that the very small helium inventory meant that the standard method of valving out the cryogenic system resulted in a pressure rate of rise too large to be useful. Despite significant effort, it was only able to put a lower limit on the quality factor of $5E8$.

LOM Tuning

The LOM damping waveguide was designed into the cavity cell itself to satisfy the APS stability requirements. This design proved quite vulnerable to symmetric effects, leading to significant deflecting mode leakage into the LOM waveguide. This test was a major verification of the tuning procedure developed to minimize this leakage. The measured $Q_{ext,2}$ stayed constant when the tuner was attached and after cooling to 2 K, indicating that the leakage remained constant as well. As currently designed, approximately 10 Watts of deflecting mode power will leak out the LOM waveguide at the operational cavity field level.

RF SYSTEMS

5-kW Amplifier and Waveguide Systems

The cavity was driven by a purpose-built 5-kW, 2.815-GHz klystron-based amplifier, built by the APS RF Group. The amplifier was connected to the cavity through a WR-284 aluminum waveguide. The cavity coupling was set to $1E6$ by a step in the FPC waveguide at the cavity flange. Given this coupling, it was expected to need 1.73 kW to operate the cavity at full field with no beam loading.

Digital Low-Level Rf

A digital low-level rf control system has been developed in collaboration with LBNL. SPX requires very tight tolerances on amplitude and phase control between cavities and between cryomodules. This test provided a first opportunity to test this system while controlling a cavity under realistic conditions. This system offers a self-excited loop mode (SEL) and generator-driven resonance (GDR) that provide open (unmodulated) and closed (phase and amplitude stabilized) modes, all of which were successfully demonstrated. Successful closed-loop performance can be seen in Figure 4.

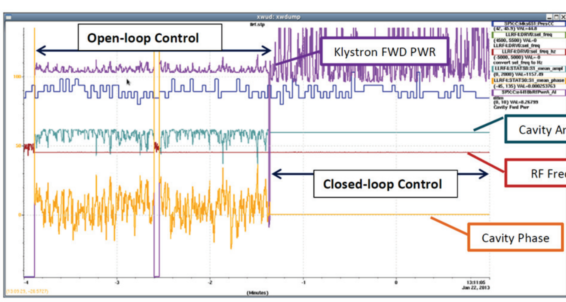

Figure 4: The closed loop performance of the SPX LLRF cavity field generator at 7 W (open loop mode), approximately 10 W (in closed loop mode) rf power level with the presence of significant microphonics in the SRF.

The digital rf system was also used to study the cavity stability and microphonics. RMS phase errors were measured at various field levels, and several sources of vibration were identified and quantified. In open-loop measurements, the ATLAS cryo-compressors were identified as the dominant source of noise at 55 Hz. In closed-loop mode, the insulating vacuum turbo-pump used on the test cryostat was seen as the dominant source of noise (see Figure 5) at 600 Hz. Even with this noise source, the LLRF system achieved better than 10-mdeg phase noise integrated up to 1 kHz, which is better than the specification for the system in operation.

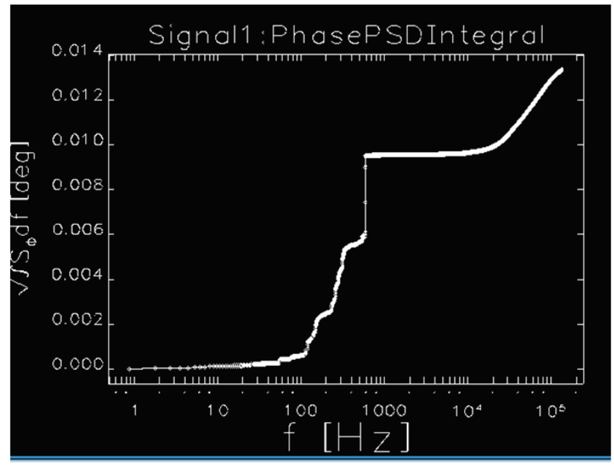

Figure 5: RMS phase noise measured “in-loop” using closed-loop mode. The large jump in noise at 600 Hz was identified as the cryostat insulating vacuum turbo pump.

TUNER PERFORMANCE

The SPX cavity tuner is a modified version of the CEBAF C100 tuner. This means that the tuning is accomplished by a stepper motor and piezo-electric actuator in series outside the cryostat. The tuning range is designed to be ± 200 kHz with a tuning resolution of 40 Hz required.

Once cold, the tuner was preloaded and exercised over its full 600-kHz range several times. After the first burn-in run, a noticeable hysteresis was still observable over the full range, but essentially negligible over spans of 25 kHz or less (see Figure 6). The slow-tuner control loop was closed and demonstrated successful frequency control (seen in Figure 7). Testing time was limited, so only minimal effort was spent optimizing the slow-tuner control loop, but the optimization that was achieved gave good confidence that the existing control system was adequate.

Cavity resolution measurements were performed by averaging frequency data after each tuner step. The resulting data can be seen in Figure 8. While the sweep was made with enough steps to traverse 3 kHz of cavity tuning range, the resulting frequency shift of the cavity varied. There was a slow drift of the cavity frequency, likely resulting from the slow temperature drift of the tuner body. Smaller step sizes took longer to perform and integrated more of this slow drift. Measurements were taken with 10-Hz steps, but while the trend was linear, it was in the opposite direction, indicating that the slow thermal drift was shifting the frequency faster than the measurement could be performed.

INSTRUMENTATION AND CONTROLS

In addition to the major subsystems, there was an extensive interlock and instrumentation system developed at ATLAS for test operation. Notably, the instrumentation, data

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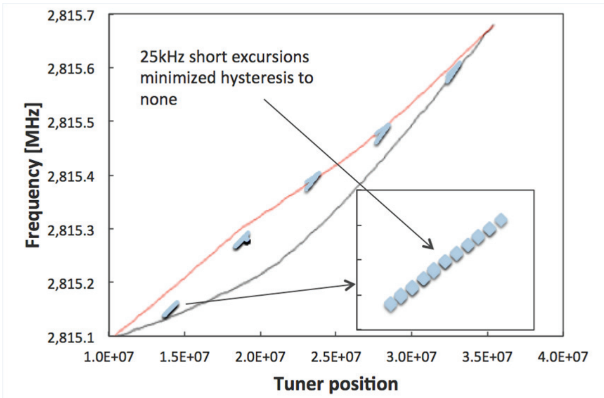

Figure 6: Tuner operation over its full range of 600 kHz and smaller spans of 25 kHz. Hysteresis is notable over the full range but negligible over the smaller spans.

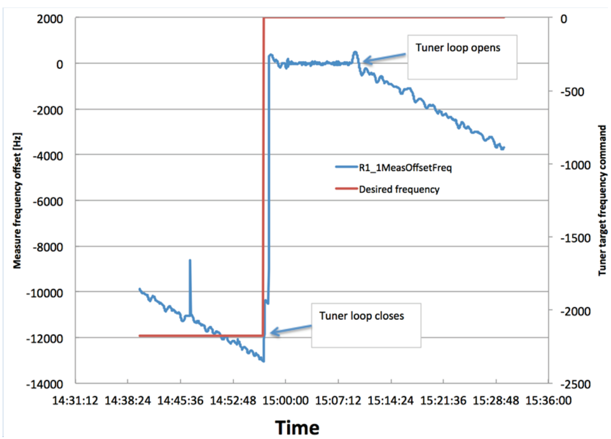

Figure 7: Cavity tuner control loop being closed and successfully regulating cavity frequency. Cavity frequency drift can be seen before the tuner control loop is closed and after it is reopened.

logging, and control software were all written in EPICS in the same style as is used for APS operations. This was done to minimize integration issues for SPX operation in the APS ring.

CONCLUSIONS

The horizontal cavity test successfully demonstrated successful performance of all cavity sub-systems, including cavity tuner and digital rf systems. Tuner resolution, phase control, and tuner control systems were measured and found to be within the specification of SPX operation. Only the ultimate cavity field was not demonstrated, and a second HCT is planned with a different cavity with demonstrated high-field performance. This test is anticipated later this year.

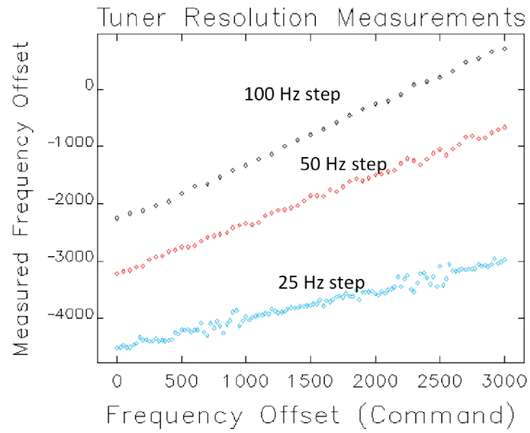

Figure 8: Three runs of the cavity tuner in steps of 100, 50, and 25 Hz. The slight change in slope is from slow thermal drift of the tuner cooling.

REFERENCES

[1] A. Zholents et al., NIM A 425,(1999)385.

[2] A. Nassiri et al., "Status of the Short-Pulse X-Ray Project at the Advanced Photon Source," IPAC 2012, New Orleans, LA, WEPPC038, p. 2292 (2012), http://www.JACoW.org

[3] Advanced Photon Source Upgrade Project - Conceptual Design Report, May 2011, http://www.aps.anl.gov/Upgrade/Documents/CDR/

[4] H. Wang et al., "Design, Prototype and Measurement of a Single-Cell Deflecting Cavity for the Advanced Photon Source," PAC 2009, Vancouver, BC, Canada, WE5PFP059, p. 2138 (2010), http://www.JACoW.org

[5] H. Wang et al., "Crab Cavity and Cryomodule Prototype Development for the Advanced Photon Source," PAC 2011, New York, NY, WEOCS7, p. 1472 (2011), http://www.JACoW.org

[6] G. Waldschmidt et al., "Status of RF Deflecting Cavity Design for the Generation of Short X-Ray Pulses in the Advanced Photon Source Storage Ring," EPAC 2006, Edinburgh, Scotland, THPLS076, p. 3460 (2006), http://www.JACoW.org

[7] G. Waldschmidt et al., "Superconducting Cavity Design for Short-Pulse X-Rays at the Advanced Photon Source," PAC 2011, New York, NY, THP212, p. 2516 (2011), http://www.JACoW.org

[8] J. Mammosser et al., "Fabrication And Testing of Deflecting Cavities For APS", FRIOA03, this conference proceedings.

[9] J. Fuerst, J. Kaluzny, "Two Low-Cost, Modular Sub-Lambda Test Cryostats," Proceedings of CEC2013, Anchorage, AK, to be published.

[10] J.M. Nixon, L.M. Bollinger, "The Liquid Helium System of ATLAS, in IEEE Proc. of 1989 Particle Accel. Conf.," PAC 1989, p. 571 (1989), http://www.JACoW.org