A SUMMARY OF THE ADVANCED PHOTON SOURCE (APS) SHORT PULSE X-RAY (SPX) R&D ACCOMPLISHMENTS*

A Nassiri#, N. Arnold, T. Berenc, M. Borland, B. Brajuskovic, D. Bromberek, J. Carwardine, G. Decker, L. Emery, J. Fuerst, J. Holzbauer, D. Horan, J. Kaluzny, J. Kerby, F. Lenkszus, R. Lill, H. Ma, V. Sajaev, B. Stillwell, G. Waldschmidt, G. Wu, M. White, Y. Yang, A. Zholents, ANL, Argonne, IL 60439, USA
P. Dhakal, J. Henry, J. Mammosser, J. Matalevich, R.A. Rimmer, H. Wang, K. Wilson, JLAB, Newport News, VA 23605, USA
J. Byrd, L. Doolittle, G. Huang, LBNL, Berkeley, CA 946720, USA
Z. Li, L. Xiao, SLAC, Menlo Park, CA 94025, USA

Abstract

The Advanced Photon Source at Argonne conducted R&D on design, fabrication, prototyping, and testing of superconducting deflecting cavities aimed at the production of short x-ray pulses at the Advanced Photon Source. In collaboration with Jefferson National Laboratory, we focused on prototyping and testing a number of single-cell deflecting cavities. At ANL, we designed, prototyped, and tested silicon carbide as damping material for higher-order-mode (HOM) dampers, which are broadband, to handle the HOM power across the frequency spectrum produced by the APS beam. In collaboration with Lawrence Berkeley National Laboratory, we have been developing state-of-the-art timing and synchronization system for distributing stable rf signals over optical fiber capable of achieving tens of femtoseconds phase drift and jitter. Collaboration with the Advanced Computations Department at Stanford Linear Accelerator Center looked into simulations of complex, multi-cavity geometries. This contribution provides a summary report on the accomplishments of the SPX R&D.

INTRODUCTION

We previously reported on SPX R&D (SPX0) [1]. The concept of using transverse superconducting rf deflecting cavities to produces high-repetition-rate picosecond x-rays with the APS has been previously described [1-3]. Since our last report in 2012, substantial progress has been made in prototyping, components testing, and performance characterization of deflecting cavities. A summary of the major technical accomplishments supported by the APS Upgrade Project is described here.

CAVITY AND CRYOMODULE

Four on-cell damped deflecting cavities (see Figure 1) were fabricated, processed and vertically tested. They were lightly etched by a standard buffered chemical polishing (BCP) process near the weld prep and joined by electron beam welding. The deflecting mode field symmetry in the on-cell damped deflecting cavities was determined to be very sensitive to geometry imperfections. Multipacting simulation indicated that poor field symmetry could result in enhanced multipacting as the field in the on-cell coupler increases. The higher field in the on-cell coupler could also increase the joint rf losses. Temperature mapping system indicated temperature rising during the multipacting events [4]. A careful tuning was needed to the tune deflecting mode field to minimize field leakage to the on-cell damping coupler. The symmetry tuning was maintained as the cavity cooled down during vertical testing. Three cavities exceeded specifications; two were chosen for helium vessel dressing and cryomodule assembly. The vertical test results of the two cavities are shown in Figure 2 [5]. Cavity performance was limited by quenches. One cavity experienced multipacting before quench events. One cavity suffered additional joint losses and did not meet the specifications. The low-performing cavity was used to test the helium vessel attachment procedures. The other two cavities were dressed and tested. Test results indicated the helium vessel attachment did not degrade the cavity performance.

Figure 1: SPX superconducting deflecting cavity.

A preliminary design of the two-cavity cryomodule has been completed as shown in Figure 3 [5]. For the cryomodule we adopted a side loading design with a space frame supporting the cavity string and nitronic rods to allow alignment control. The tuner is a shortened design of the CEBAF scissor-jack tuner. Its slow tuner provides a ±200-kHz tuning range and better than 40-Hz resolution when attached to a highly sensitive dressed

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#nassiri@aps.anl.gov

deflecting cavity. A piezo actuator is built into the tuner system to provide super-high-resolution tuning, fast detuning, and possible active microphonics compensation when needed. Both slower tuner motor and piezo actuators are located in the warm section and are external to the cryomodule.

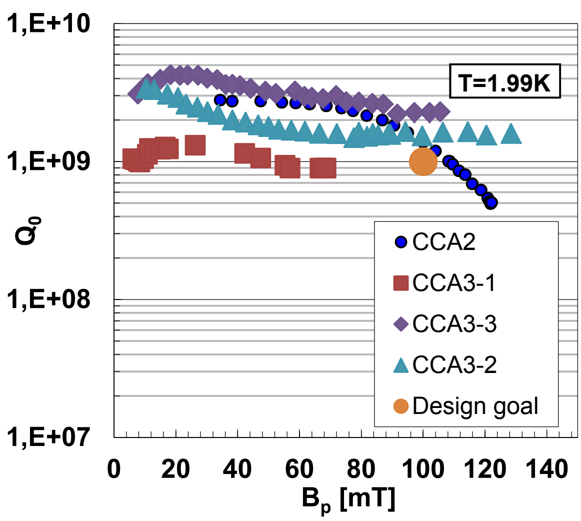


Figure 2: Performance results of four SPX deflecting cavities.

The horizontal test of a dressed cavity with tuner indicated the cavity system without dampers worked exceptionally well; all subsystems worked flawlessly to provide a well-controlled deflecting cavity operation in a horizontal fashion nearly identical to cryomodule settings [6]. Those subsystems include the cavity, helium vessel, tuner, piezo detuner, low-level rf control, and high-level rf system.

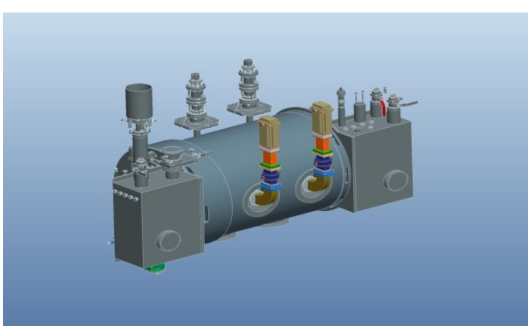
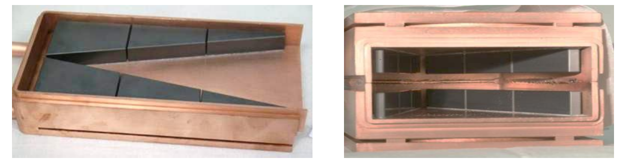


Figure 3: A preliminary design of a 2-cavity cryomodule.

DAMPERS AND WAVEGUIDES

The dampers for the R&D phase of the SPX (SPX0) consist of iso-pressed silicon carbide (SiC) material from St. Gobain due to its rf, mechanical, and vacuum properties. It is a lossy ceramic material with an average loss tangent of approximately 0.1 and relative permittivity of approximately 11.5 across the SPX0 frequency band. Electrical material properties that were evaluated from various vendors, manufacturing methods, and fabrication batches were found to be consistent. During the fabrication of the dampers, slabs of SiC were cut into multiple 50-mm wedge-shaped tiles for soldering onto the copper waveguide bodies, as shown in Figure 4. The detailed fabrication process and test results are summarized in [7].



(a) (b)

Figure 4: HOM damper assemblies: (a) copper damper half with soldered SiC tiles and (b) E-beam welded prototype damper assembly.

RF SYSTEM

A 2.815-GHz/5-kW cw rf power amplifier system was designed and built for the SPX0 effort. The amplifier utilizes a conventional klystron output device with permanent-magnet focusing, and includes a complete rf interlock system to provide equipment protection for internal amplifier components and personnel protection against high-voltage and rf-radiation hazards. The amplifier output waveguide system also includes two waveguide shutters to provide key-lock protection against personnel exposure to rf power downstream of the amplifier, and an internal 5-kW test load and waveguide switch to provide the capability for full-power testing of the amplifier without disassembling any part of the waveguide system. Figure 5 shows a completed 5-kW amplifier system used for horizontal deflecting cavity tests.

Figure 5: A 5-kW S-band rf amplifier system for SPX0.

The SPX0 low-level rf (LLRF) system has to meet the most stringent rf phase stability specification of 0.038 deg rms differential phase error between two deflecting cavity sectors. In collaboration with LBNL, the SPX0 LLRF system was designed to meet the phase stability requirement. The system developed will stabilize the cavity rf field with a digital LLRF controller with respect to an rf phase reference distributed via fiber to synchronization heads at the cryomodule in the tunnel. While the timing-synchronization system monitors and

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calibrates the phase drifts along the fiber cables, the LLRF controller monitors and calibrates the phase drifts along the rf signal transmission coaxial cables between the sync-head and the LLRF controllers. The key electronics technology for this system is an advanced implementation of the multi-frequency channel digital transceiver in which the rf cable phase drift is measured and compensated for with an rf pilot-tone.

TIMING AND SYNCHRONIZATION

Since the timing and synchronization system was last reported [8], four synchronization heads—three rf and one optical—have been manufactured and tested. In addition, all chassis for the 16-channel transmitter/sender; i.e., the cw laser oscillator, rubidium (Rb) locker, modulator, and EDFA amplifier and sender, have been manufactured and tested.

The sync heads are constructed with a double case with thermal insulation between the two cases (see Figure 6).

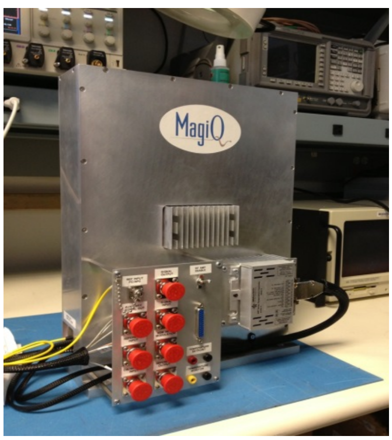

Figure 6: The rf synchronization head.

The internal temperature of the sync head is regulated to ±0.01°C to minimize temperature effects on the internal components. The rf sync head accepts as input the field probe signal of a cavity. The optical sync head provides an optical input that will be coupled to a beamline laser oscillator optical output to sample the phase.

A critical requirement for the transmitter sender is the frequency stability of the cw laser oscillator. The wavelength of the cw laser is locked to a hyperfine absorption line of rubidium to stabilize the wavelength. The stability of the cw laser/Rb locker was measured by beating it against another stabilized cw laser oscillator. The frequency stability was measured to be 2.3×10^{-9}. This frequency stability will contribute less than a 4-fs error to synchronization for the longest (300 m) fiber cable planned for SPX.

A two-channel test using two rf sync heads and two LLRF receivers with the transmitter/sender is planned at LBNL. One receiver will regulate the phase of a 2815-MHz vcxo, and the second receiver will be used to do an out-of-band measurement of noise and stability.

MECHANICAL SUPPORT

The effort toward testing the SPX0 cryomodule in the APS storage ring has involved the design of a considerable amount of hardware, much of it fabricated. The straight section assembly needed to physically integrate the SPX0 cryomodule into the storage ring vacuum system was built and tested offline (see Figure 7). The system consists of a 2.5-m-long insertion device vacuum chamber (IDVC) including a tapered transition from the IDVC aperture to the 52-mm-diameter cryomodule beam tube aperture; a water-cooled photon absorber to shield SPX systems from bending magnet radiation; an rf-shielded gate valve to isolate the IDVC from cryomodule installation and removal operations; spools to substitute for the cryomodule when it is not in place; a special tapered chamber to transition from the cryomodule beam tube aperture to the APS accelerator chamber aperture; ultra-high vacuum pumps and gauges; and various minor vacuum and mechanical support hardware.

Figure 7: SPX0 straight section vacuum system.

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