FABRICATION AND TESTING OF DEFLECTING CAVITIES FOR APS*

J. Mammosser†, H. Wang, R. Rimmer, J. Henry, K. Wilson, P. Dhakal,
A. Nassiri‡, J. Kerby‡, J. Holzbauer‡, G Wu‡, J. Fuerst‡, Y. Yang‡, G. Waldschmidt‡, Z. Li‖, F. He♠
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA
‡Argonne National Laboratory, Argonne, IL 60439, USA
‖SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA
♠Peking University, Bejing, China

Abstract

Jefferson Lab (Newport News, Virginia) in collaboration with Argonne National Laboratory (Argonne, IL) has fabricated and tested four first article, 2.8 GHz, deflecting SRF cavities, for Argonne's Short-Pulse X-ray (SPX) project. These cavities are unique in many ways including the fabrication in which the cavity cell and waveguides were fabricated. These cavity subcomponents were milled from bulk large grain niobium ingot material directly from 3D CAD files. No forming of sub components was used with the exception of the beam-pipes. The challenging cavity and helium vessel design results from the stringent RF performance requirements required by the project and operation in the APS ring. Production challenges and fabrication techniques as well as testing results will be discussed in this paper.

SHORT PULSE X-RAY CONCEPT

The Short Pulse X-ray [1] concept for the Advanced Photon Source (APS) ring consists of two sets of deflecting cavities to be located in straight sections of the APS ring. The deflecting cavities operate at a harmonic of the ring RF frequency allowing the first set of cavities to chirp the beam, adding a correlation between electron longitudinal position and transverse momentum. X-Rays produced by this bunch will also have this correlation, and can be put through transverse slits to produce pulses of X-Rays 1-2% the duration of those currently available to users. The second set of cavities are located a multiple of 180 degrees of phase advance down stream and allow for the beam to be unchirped, removing the effects of the first cavity set. In this design scheme, a section of the APS machine can be used for short pulse experiments without affecting the rest of the experiments around the ring. In Figure 1, a schematic of the deflecting cavity process is shown.

SPX CAVITY DESIGN

The cavity has a flattened oval shape and operates in the TM110 mode. This mode has strong magnetic fields in each lobe of the cell and a strong, transverse magnetic field on the beam axis. This magnetic field is used to add the longitudinal position/transverse momentum correlation in the vertical plane. The RF power is fed from a fundamental power coupler (FPC) waveguide which forms one of the legs of a "Y" end-group attached to the cell. Two higher order mode (HOM) waveguides, "A" and "B" form the other two legs of the end-group, each rotated 120 degrees from the FPC. Two cavity designs were prototyped, one with a lower order mode (LOM) waveguide off-cell on the opposite side of the FPC and one with the waveguide directly into the cavity cell, called the on-cell LOM. This on-cell cavity design can be seen in Figure 2.

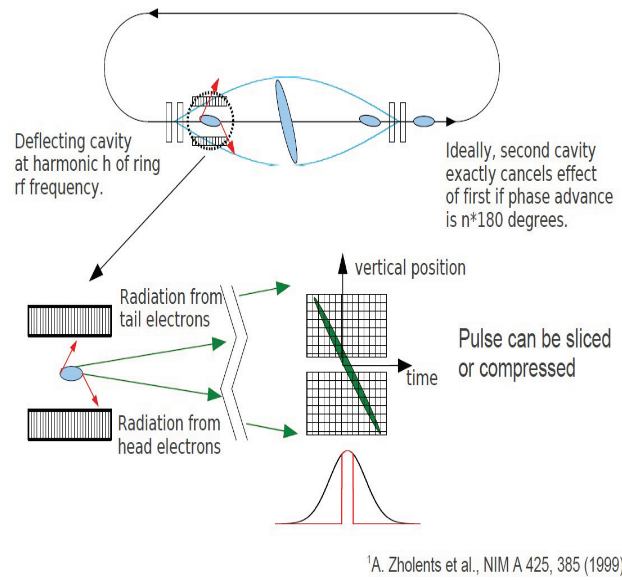

Figure 1: SPX Design Concept.

Cavity Requirements

The deflecting cavity has many critical performance requirements for the APS ring, which will operate in two types of beam modes up to 150 mA of beam current. The deflecting cavity must produce 0.5 MV of deflecting voltage requiring 100 mT of peak surface magnetic field, to keep the cryostat length short due to limited beamline space. Given the high beam current, ring stability and availability requirements made this an extremely challenging

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† johnm@jlab.org

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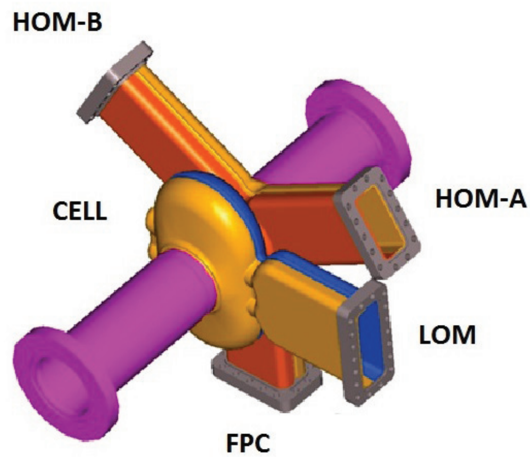

Figure 2: On-Cell Cavity Model.

design for an SRF deflecting cavity, especially considering the stringent wakefield damping requirements.

Space concerns required a cavity and overall design that could stay with the tight space envelope available in the APS tunnel. The main concerns starting the program were achieving the deflecting voltage routinely and maintaining thermal and mechanical stability of the cavity system in the ring during operation. These concerns of performance and packaging drove the design of the cavity and helium vessel and fabrication methods. The key cavity performance requirements are listed in Table 1.

Table 1: SPX Deflecting Cavity Parameters Subset

Cavity Design	Parameters	Units
Freq. of Deflecting Mode	2815.488	MHz
Duty Cycle	CW (8th Harmonic)	
Geometric factor	227.8	Ω
Active length	53.24	mm
Rt/Q	37.1	Ω
Cavity Overall Length	389.76	mm
Cavity Deflecting Voltage	0.5	MV
APS Beam Current	150	mA
Beam Pipe Aperture	52	mm
Cavity Iris Aperature	50	mm
Peak E-field (E_P^*)	40.8	MV/m
Peak B-field Vertical Test	105	mT
Alignment Cavity to Cavity	Electrical Center	
X misalignment	± 500	μm
Y misalignment	± 200	μm
Z misalignment	± 1000	μm
Yaw misalignment	± 10	mrad
Pitch misalignment	± 10	mrad
Roll misalignment	± 10	mrad

Waveguide Design

In the on-cell design, the LOM power is coupled out of the cell through a small iris shaped as a dog bone. On the opposite side of the cell, an additional dog bone feature was added to symmetrize the cavity fields. Although both on-cell and off-cell LOM designs were prototyped, the on-cell LOM waveguide design was chosen due to its increased margin in beam stability due to lower monopole impedance from wake field simulations. The on-cell LOM waveguide can be see in Figure 3 during cavity fabrication.

Figure 3: Machining of an on-cell LOM cavity half in 5-axis mill.

Subassembly Fabrication

Due to the complicated shapes of this design it was decided to directly machine the cell and waveguide subcomponents from ingot material. The concern was that if the cell shape was distorted, the deflecting mode would be coupled too strongly out of the LOM waveguide due to asymmetry of the cell. This coupling error can only be recovered by tuning of the cell and distorting the fields or changing the shape of the dogbone iris to reject the deflecting mode. This fabrication method raised possible concerns that the cavity might not reach the specified 105 mT deflecting magnetic field due to contamination from the tool machining of the entire cavity surface. The 105mT field was chosen for the vertical test specification and 100mT filed is needed in APS.

These concerns were addressed by the prototyping and testing of cavity CCA2, fabricated as a proof of principle. To start the fabrication, the cavity and waveguide shapes were cut from a large grain niobium ingot. Figures 3, 4, 5, and 6 show various stages of the cell and waveguide fabrication. Several tooling dies were made to hold the individual components through all the critical machining steps to reduce errors due to flexing and vibration. Figure 7 shows two of the finished cavities, CCA3-1 and CCA3-2.

The niobium ingot, RRR of ¿150 was cut with wire EDM to maximize the use of the ingot and reduce material loss due to machining. For the machining of the cell and waveg-

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uide halves, models were directly downloaded to each of the machine tools to perform machining tasks. For the machining a 5 axis mill was utilized but only 3 axis were required in the machine tool operation. The machined cell surfaces were then measured on the CMM to verify their profile and good repeatability was achieved with 0.5 mil tolerances. The machining took many hours but the non critical steps such as the rough cutting were performed overnight to reduce labor hours. Inspection of the finished components showed the machining could give a adequate surface finish of better then 50 microns if machining tools were replaced routinely as indicated from tool loading indicators.

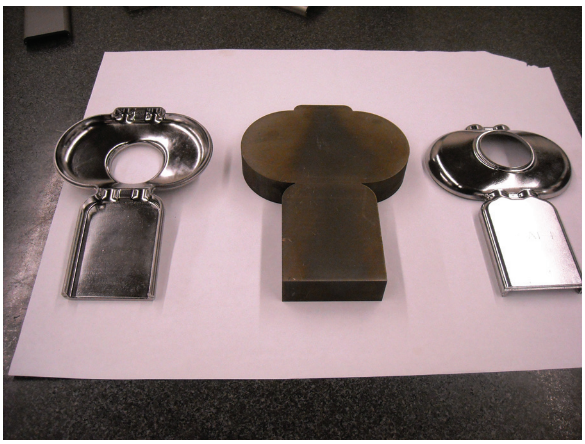

Figure 4: Cell fabrication with niobium blank shown in center.

Figure 5: "Y" Waveguide niobium blank.

CAVITY RF PERFORMANCE

Four first article cavities were fabricated for development and demonstration of SPX concept. The four cavities designated CCA2, CCA3-1, CCA3-2 and CCA3-3. The CCA3 cavities were designed and fabricated to be dressed with a helium vessel. All cavities were tested in the vertical test for qualification and cavities CCA3-1 and CCA3-2

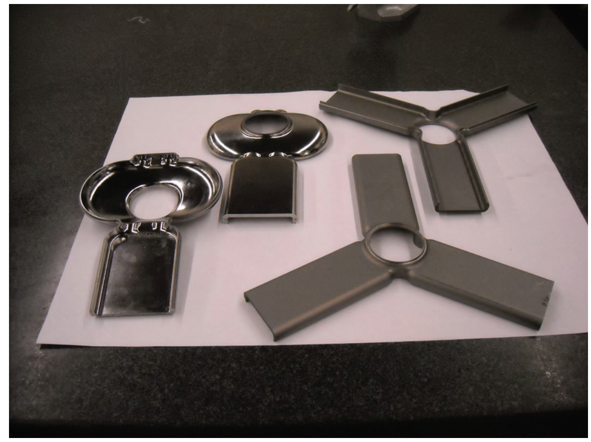

Figure 6: Cells and waveguides subassemblies after machining was completed.

Figure 7: CCA3-1 and CCA3-2 finished cavities.

were completed with helium vessels to date to develop procedures and verify horizontal performance in a test cryostat at ANL. The horizontal tests were aimed at understanding the operation of the cavities closer to the machine configuration and verifying the operational stability and thermal design. Vertical tests were performed at both JLAB and ANL each focusing on developing understanding of the cavity performance limitations.

All of the cavities had bulk material removal by BCP. Cavities CCA3-1, 2 and 3 were fully processed at Cornell University using their production chemistry system followed by furnace treatment and internal inspection. The internal inspection discovered that two of the cavities had welds on the sharp turn in the dog-bone equator that were not fully penetrated. These areas were locally remelted by electron beam welding aimed through the LOM waveguide into the cavity cell.

Each cavity was vertically tested multiple times, to develop an understanding of the RF performance and to push the peak surface magnetic field to the specifications of 105 mT. Typical processing procedures of degreasing, light BCP and high pressure rinsing were used followed by careful assembly in the cleanroom. The cavity testing started with beam axis coupling which turned out to be very sensitive to set and maintain the Qext. For repeatability, niobium top-hats were fabricated for both the FPC and LOM waveguides and were used for subsequent tests. All vacuum seals on flanges were indium with the exception of an aluminum diamond seal on the beampipes and the field probe.

Initial Cavity Performance

Early cavity test results showed a number of problems such as early quenches, Q-switches, thermal heating lowering the Q-value and poor low-field Qo. Q-switching typically started with a normal Q-value 1e9 falling to 5e8 values and recovery only after lowering the field in the cavity significantly. Retesting of each cavity resulted in a vastly different performance and it took some time to understand the causes of the variability. Light multipacting occurred in most tests starting around 40mT fields and processing out to an ultimate quench limit typically below the 105 mT qualification limit. No X-rays were seen in most tests due to the low energy gain across the cell, although one test of a cavity that had been vented to cleanroom air showed significant x-ray production at high fields.

Typically tests were stopped once a quench was reached and cavities were internally inspected after disassembly, reprocessed and vertical tests repeated. Several process steps were added over this period such as low temperature baking and additional high pressure rinsing and degreasing. Cavity performances did start improving but still repeatability of performance was low. After one of the baked cavity tests it was noticed that the Q-switch gradient had moved out to a much higher field level.

LOM Tuning

The first horizontal test of CCA3-1 showed heating at the LOM strongly correlated with a strong Q-switch. These clues lead to additional electromagnetic modeling of the cavity and coupling of fields in the waveguides, monitoring the tuning of the cell at multiple stages of assembly and testing as well as studying the effect on multipacting in the LOM, HOM, and cell. A LOM tuning procedure was developed to plastically deform the cavity cell asymmetrically while monitoring the deflecting mode leakage into the LOM with the goal of minimizing the leakage. Tuning the LOM this way could repeatably achieve deflecting mode coupling to the LOM of better than $Q_{ext,LOM} > 1E10^8$. This tuning eliminated the observed low Q-values and significantly improved cavity performances.

Additionally, a cavity test which had been limited by quench had its LOM waveguide tuned, and presented significantly improved performance and was much more responsive to RF processing. This pointed to the possibility that the quench had been induced by multipacting. Cavity modeling also showed that the deflecting mode coupling into the LOM waveguide could cause heating at the LOM flange and vacuum seal joints, and could also enhance multipacting in the cell at the dogbone location by changing fields in the cavity. This multipacting could then lead to a quench in the cell at the dog bone short location. Results of multipacting simulations done at SLAC can be seen in Figure 8 shows the locations of multipacting at the dogbone region with cavity asymmetric field LOM leakage due to a artificial dent placed in the model. Figure 9 shows the graph of electron stable trajectories.

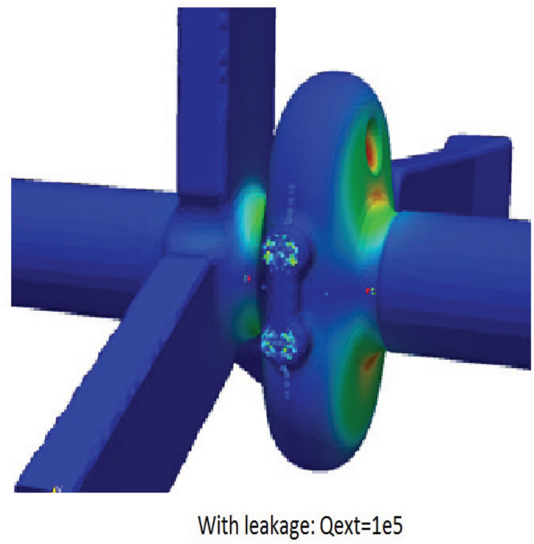

Figure 8: Locations for Multipacting with asymmetric fields in cavity.

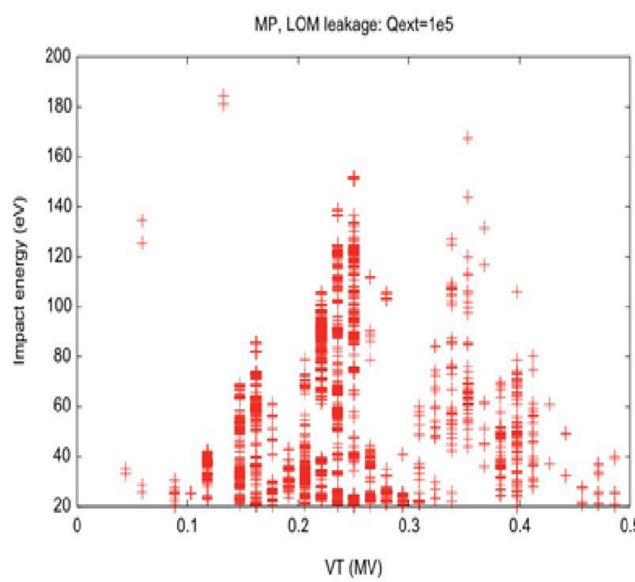

Figure 9: Resulting multipacting bands with asymmetric fields.

To resolve all these issues, the cavity cell LOM tuning was tracked through the process steps. This coupling was found to be very sensitive to mechanical changes to the cavity from center frequency tuning, cavity handling,

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and chemistry. Any distortion caused an asymmetry of the fields in the cell and increased the deflecting mode in the LOM waveguide. Further cavity tests that ended in a quench were carefully tested to see if improvements from RF processing could be gained. These steps increased the overall performances of the cavities and three of the four reached 105mT or greater. The only cavity that was not qualified was CCA3-1 which was used for the first horizontal test and was not further processed. Distortions from helium vessel welding also significantly changed the cell tuning and there was no access to cell for plastically tuning. A plot of the current cavity performances can been seen in Figure 10.

For the horizontal test, an CEBAF upgrade type scissor jack tuner was fabricated and tested in the horizontal test. In order to preserve the LOM waveguide tuning for the dressed cavity case, the tuner fulcrum bars were adjusted to provide a slight offset from one side to the other and this was enough to reduce LOM coupling errors from the helium vessel welding. This method was successfully demonstrated in horizontal testing when qualifying the tuner design performance.

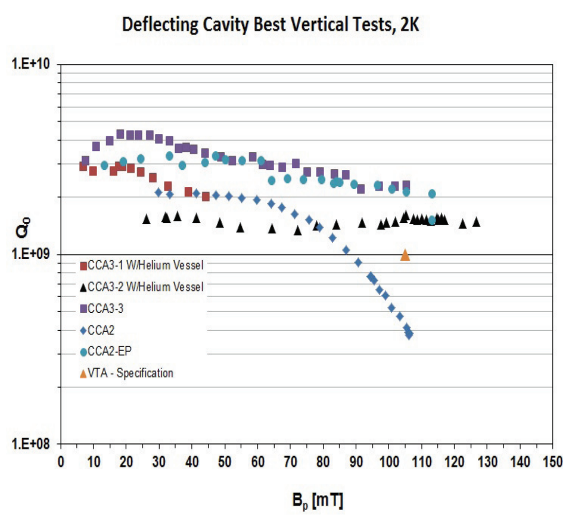

Figure 10: Cavity Vertical Test Best Data.

HELIUM VESSEL DEVELOPMENT

The helium vessel design for the deflecting cavity was quite complicated due to the compactness of the cavity and the number of waveguides. Titanium material was chosen for the helium vessel due to the frequency sensitivity of the cavity which had been measured to be about 10 MHz/mm. This meant that thermal contraction could detune the cavity and LOM tuning; using titanium provided a good thermal match to reduce these effects. The cavity waveguide lengths and positions were defined by the RF and thermal design. The resulting geometry required integrating them inside the vessel to increase the liquid volume of each cavity for operational stability. The cold magnetic shielding was integrated inside the helium vessel as well to provide the best shielding of magnetic fields due to the direct line of sight into the cell from the multiple waveguides.

The cavity design was very stiff and modeling showed the helium vessel would increase the stiffness even more and lock the waveguides into place, placing additional constraints on the tuner. These design choices resulted in a vessel of many pieces that would be patched together by tig welding. An additional complication to this fabrication was the distortion of the cavity waveguides due to the number of electron beam welds in such a small structure. Waveguides were misaligned by up to a few millimeters and this would complicate the the stack up of components and tacking of the assembly. Each waveguide would had a NbTi transition flange that provided a weld ”V” for full penetration welds. Several problems were encountered with the helium vessel welding and the first attempt failed due to limited access for purging under flanges due to the limited space.

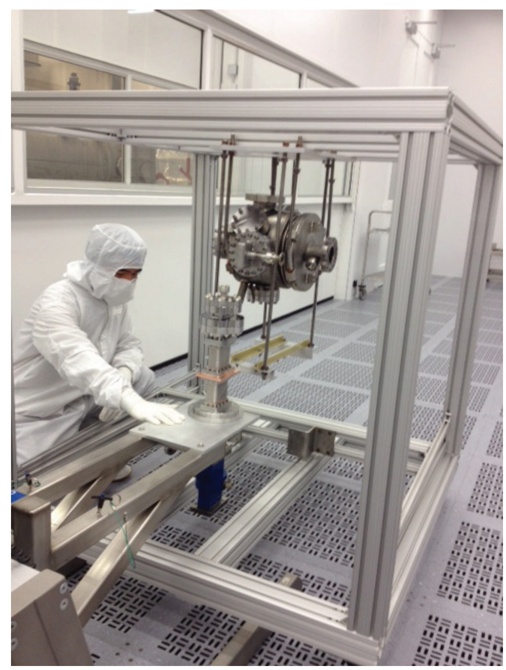

Figure 11: Assembly of CCA3-1 for Horizontal Testing at ATLAS.

To get around this problem the flanges were removed by wire EDM. The first cavity CCA3-1 was taken to ORNL code shop for the repair and completion to meet the horizontal test schedule. This cavity was used for the horizontal testing of the tuner and LLRF system. The helium vessel design was changed to reduce the size of the vessel bellows and reduce the risk for plastically deforming the cavity in the event of a helium pressure excursion. The bellows size was reduced from 10 inch ID to 4.75 inch ID. This change further complicated the welding sequence. The cavity CCA3-2 was welded at JLab with this new design. A leak developed in the small bellows due to arc discharge through the bellows first convolution. When this was discovered the design was changed to add an additional shield behind the NbTi transition due to the close proximity to the first bellows convolution. The cavity bellows was replaced and the cavity was completed and made ready for horizontal testing.

HORIZONTAL TEST RESULTS

The cavity CCA3-1 was tested at ATLAS test facility in the horizontal test cryostat. The goal of this test was to verify the cavity performance under RF and thermal conditions close to cryomodule operations and to verify cavity operation with many of the subsystems being developed for SPX. These subsystems included a specially designed digital low-level RF system, a purpose built 5 kW amplifier, and the cavity tuner controller and operation. Assembly of the CCA3-1 cavity for horizontal test can be seen in Figure 11.

The cavity testing spanned several days and many areas of the SPX operational performance were explored and many new technical challenges were identified. While a full description of the test and results can be found in reference [2], the cavity showed no degradation in achievable field level (75 mT) and was shown to be thermally stable operating at that field level. The LOM tuning was monitored during the whole test, and tuner assembly, thermal cycling, and tuner operation had no effect on LOM leakage. The thermal data was used to understand where improvements were needed for the cryomodule thermal design and to better understand the cavity performance.

CONCLUSION

Four superconducting deflecting cavities were designed, fabricated and tested for the demonstration of the short pulse X-Ray experiments in the APS ring. All cavities have been vertically tested to develop an understanding of this type cavity and to progress the cavity limits towards the design goal of 105 mT peak surface magnetic field. Three of the four cavities achieved this goal in vertical testing at both ANL and JLAB. Two cavities were fully dressed with helium vessels and one was horizontally tested at ANL. Many challenges were encountered during fabrication and RF testing of these cavities and solutions were developed to overcome them, resulting in a successful cavity design for ANL's SPX application. Additionally, JLAB and ANL had a successful collaboration in this project sharing both expertise and facilities while developing a better understanding of this technology throughout this challenging project.

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