DEVELOPING QUARTER WAVE SRF CAVITIES FOR HADRON COLLIDERS*

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Abstract

Recently, the application of QWRs has carried over into hadron colliders, aiming at various goals. A 56 MHz superconducting QWR is undergoing tests at Brookhaven National Laboratory (BNL). It will be installed in the Relativistic Hadron Ion Collider (RHIC) as a storage cavity, which would be the first QWR operating in a high energy storage ring. BNL and Niowave, Inc. have designed, fabricated, and tested a 112 MHz quarter wave resonator electron gun with cryomodule. This is the lowest frequency SRF gun ever tested successfully. A compact crab cavity using QWR concept is another active superconducting RF (SRF) project at BNL. It is a candidate for the Large Hadron Collider HiLumi upgrade. There are also other QWR designs initiated at BNL, e.g. the electron gun and booster cavity for the Low Energy RHIC electron Cooling (LEReC) project, both operating at 84.5 MHz. I discuss the design, fabrication, and testing results for the QWRs for the hadron colliders under development at BNL.

INTRODUCTION

Quarter Wave Resonators (QWRs) are widely used in low-beta accelerators worldwide because of their compact size at low frequencies [1]. The high-energy hadron colliders can adopt the same merit for various applications including the storage cavity and a deflecting (crab) cavity. Both applications now are under development. In the Relativistic Hadron Ion Collider (RHIC) at Brookhaven National Laboratory (BNL), we designed a 56 MHz superconducting QWR as a storage cavity for RHIC [2]. The cavity is being tested in the new vertical test facility. This passive resonator, together with the existing 28MHz accelerating cavity, offers a larger longitudinal phase space area and accommodates a larger energy spread of the ion beam than before. With the installation of this QWR in RHIC, we expect a 50% increase of RHIC's luminosity [3]. It will be the first QWR operating in a high-energy storage ring. A QWR SRF electron gun tested at the frequency of 112 MHz for the Coherent Electron Cooling (CeC) of RHIC [4, 5]. This long wave length allows the generation of long electron bunches, thus minimizing space charge effects and enabling a high bunch charge [6].

Meanwhile, we also proposed installing a compact deflecting (crab) cavity using the QWR concept to realize crab crossing at the interaction point (IP) of a hadron collider [7, 8]. This crab cavity is a candidate for the Large Hadron Collider (LHC) HiLumi upgrade, and for the future electron-ion colliders.

* Work is supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. DOE and funding from the European Commission under the FP7 project HiLumi LHC, GA no.284404, co-funded by the DOE, USA.
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STORAGE CAVITY

To improve the luminosity of RHIC, a superconducting RF (SRF) cavity at the frequency of 56.29884 MHz was designed [9]. The cavity will be operated at harmonic 720 of the revolution frequency of RHIC, and at the temperature of 4.2 K. The cavity is a Quarter-Wave Resonator (QWR) with the beam traversing its own symmetric axis. At such low frequency, the QWR offers a very compact structure, yet very high shunt impedance. The cavity is designed with corrugations along the outermost shell to prevent multipacting [10]. Figure 1 shows the cross-sectional view of the cavity with its helium vessel.

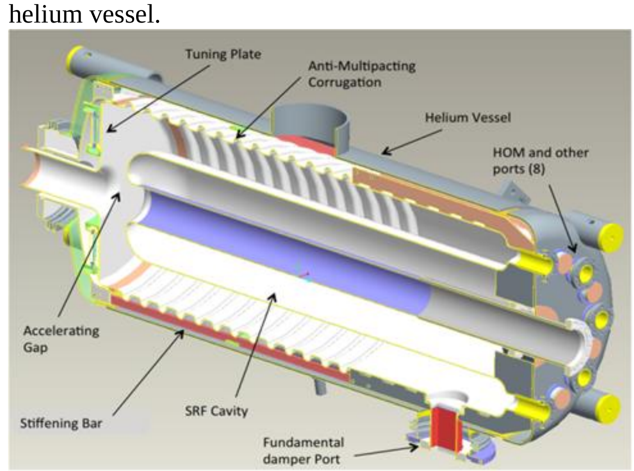

Figure 1: Layout of 56 MHz SRF QWR with helium vessel.

Table 1: Basic Parameters for 56 MHz SRF Cavity

Parameter	Value	Unit
Frequency	56.2887	MHz
Gap voltage	2	MV
Stored energy	140	J
Q_0	2.5E9	
R/Q (accelerator notation)	80.5	Ohm
Max surface electric field	35	MV/m
Max surface magnetic field	84	mT

The cavity will be beam driven, but with a 1kW amplifier connected to control the gap voltage amplitude. A fundamental mode damper (FD) would be inserted to heavily damp the cavity during beam acceleration, and extracted when beam is put into store. The FD is inserted

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from a port on the cavity's side, which is perpendicular to the cavity axis.

At the rear of the cavity, i.e. the opposite side of the gap, the cavity has eight small ports. The ports are used for chemical cleaning and higher pressure water rinsing prior to assembly, and are to be occupied by four Higher Order Mode (HOM) couplers, a Fundamental Power Coupler (FPC), a Pick-Up probe (PU), and two Infrared (IR) detectors.

Table 1 lists some basic parameters of the cavity.

Tuning

The cavity is tuned by pushing or pulling on the flat tuning plate that changes the gap. A stepper motor is used for the slow (coarse) tuning of the cavity frequency. The elastic tuning range is ±25.5 kHz with a speed of 3666 Hz/sec. Fine tuning is driven by a piezo element with a range of 60 Hz.

Fundamental Power Coupler

The FPC for this beam-driven cavity was designed as a fast tuner to stabilize the amplitude at an optimized value when the cavity's resonant frequency changes [11]. Together with the Pick-Up, the RF feedback loop also contains a 1kW power amplifier and electronic controls. The FPC frequency tuning is a fast response, supplementary to the tuning plate, in which the response time is limited by the mechanical movement of the piezo materials.

Figure 2 shows the FPC with its motion system installed on the cavity port.

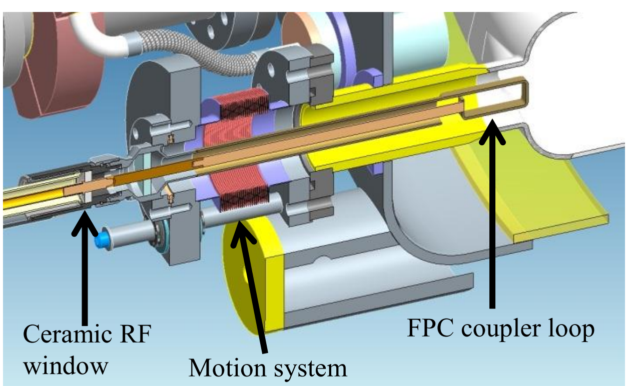

Figure 2: FPC and its motion system.

Higher Order Mode Couplers

For a passive storage cavity, the design of the Higher Order Mode (HOM) coupler assembly is the most challenging among all aspects for the 56MHz QWR [12].

We adopted for the design of the HOM coupler a rectangular loop with an opening area of 6 cm × 2.88 cm. The width of the loop was set as 2 cm and its thickness at 0.3 cm. The size of the coupler loop was designed to assure good coupling, while also allowing enough clearance for installing the coupler through the 4 cm diameter opening of the port.

To provide sufficient coupling to all HOMs with different field configurations, we installed four couplers asymmetrically as illustrated in Figure 3. In this scheme, the bottom HOM coupler is rotated clockwise by 45 degrees, so that it will couple strongly with the quadrupole modes missed by the other three couplers. Figure 4 shows that the Q_{ext} of all HOMs in such asymmetrical configurations are under 10^5.

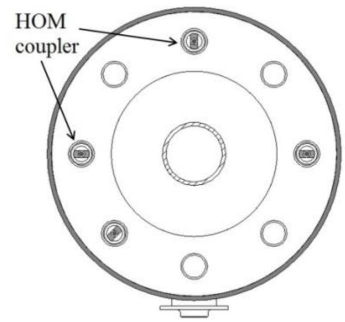

Figure 3: Configuration of four HOM couplers in the 56 MHz cavity.

A high pass filter is connected directly to the HOM coupler loop. The filter reflects the fundamental mode while transmitting the HOM power with small attenuation. We designed the filter as a three-stage high-pass Chebyshev T-type to obtain a steep roll-off and minimize the error between the designed and the actual object, Figure 5.

Figure 6 shows the simulations results of the high pass filter. The solid line is the response from an equivalent RLC circuit. The simulated transmission parameter S21 of the 3D high pass filter model for all the cavity modes below 1 GHz also appears in the same figure as solid squares. Initially, the simulation of the model and the lumped circuit match well, but differences develop in modes around 830 MHz that are due to additional capacitance contributed by the filter enclosure. However, both results show more than a 70 dB attenuation in the fundamental mode's power, and less than a 10 dB reduction for all HOMs except the four modes around 830 MHz; nevertheless, they display a reduction below 25 dB.

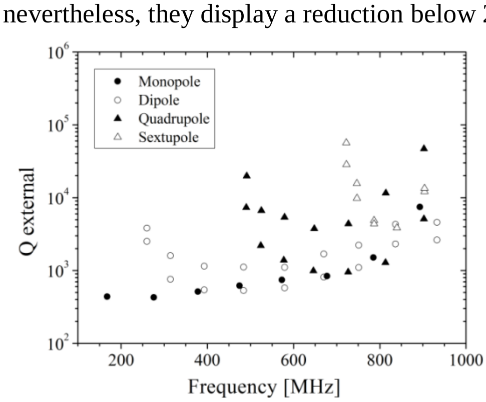

Figure 4: HOM damping with four couplers.

The 56 MHz SRF cavity is currently under vertical testing at BNL, and will be installed into RHIC by the end of 2013 [13].

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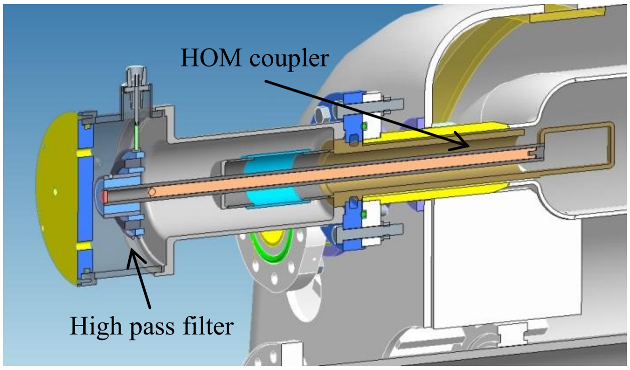

Figure 5: HOM coupler with high pass filter installed on the cavity port.

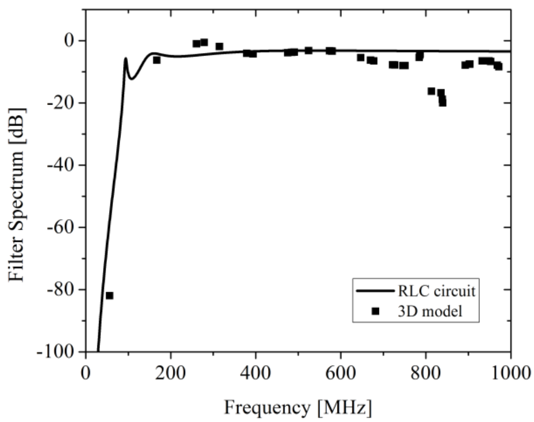

Figure 6: Performance of high-pass filter simulated with an equivalent RLC circuit and 3D simulation.

ELECTRON GUN

The 112 MHz QWR gun was designed, fabricated and cold-tested at 4.5 K in collaboration between BNL and Niowave. This is the lowest frequency SRF gun ever tested successfully [5]. Figure 7 shows the gun with its cryomodule. A Pierce-type geometry is used at the tip of the electrode nose cone to provide focusing and compensate for space charge of the high intensity electron beam. Table 2 lists the basic parameters for the 112 MHz electron gun.

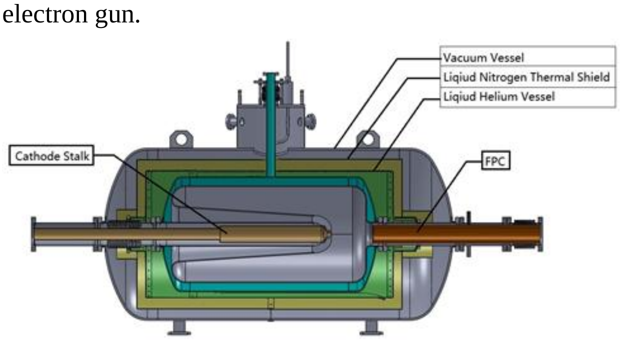

Figure 7: 112 MHz QWR with cryomodule.

The first cold test was performed at Niowave. A copper rod was inserted through the cathode insert to input RF power. We encountered MP at a few field levels, but were able to condition it through pulsed mode. The measured Q_0 is shown in Figure 8 under CW mode.

The cavity Q_0 measured as high as 1.7×10^9 at the gap voltage of 0.65 MV. The test was seized at 0.92 MV due to the limit in radiation shielding. No cavity quench was seen at high field. The designed value of the gap voltage is 1.5 to 2.5 MV, and cavity will be tested at BNL with better radiation shielding.

Table 2: 112 MHz Electron Gun Parameters

Parameter	Value	Unit
Frequency	112	MHz
R/Q (accelerator notation)	126	Ohm
Q_0	3.5e9	
Length	1100	mm
Aperture	100	mm
Max diameter	420	mm
E_{pk}/V_{acc}	19.1	m^{-1}
E_{pk}/E_{cath}	2.63	
B_{pk}/V_{acc}	36.4	mT/MV

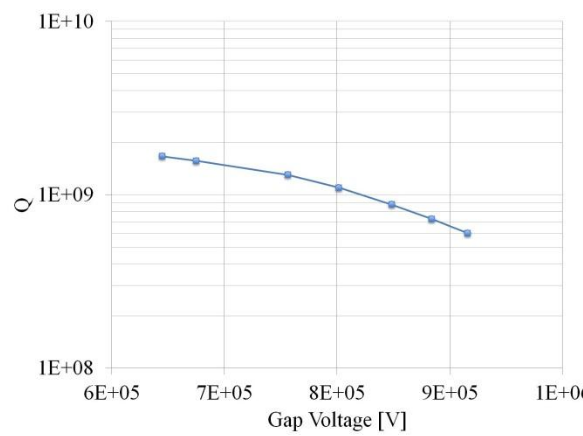

Figure 8: 112 MHz gun measured Q versus gap voltage.

CRAB CAVITY

The crab cavity first was introduced in High Energy Accelerator Research Organisation (KEK) lepton collider [14]. It recovers the loss in luminosity due to a finite crossing angle included at the IP of a collider, and minimizes the beam-beam effect of the collision.

A new concept of using a double quarter wave superconducting cavity at 400 MHz was proposed for the Large Hadron Collider (LHC) HiLumi upgrade [15]. The spacing constraints at the interaction region limited the size of the crab cavity, and eliminated use of conventional elliptical crab cavity designs similar to those used at KEK. The double quarter wave crab cavity (DQWCC) inherited the compactness in size while providing a high deflecting field (3.3 MV deflecting voltage per cavity).

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Being in the quarter wave cavity family, the DQWCC has a single gap that is contributed by two quarter wave cavities facing against each other. A large-capacitance deflecting field is generated in the gap. For the given frequency, 400 MHz, the heavy capacitive loading design lowered the equivalent inductance, and therefore, reduced the size of the cavity further.

Proof of Principle Cavity

As the first stage of our new concept of the crab cavity, we designed a Proof of Principle (PoP) DQWCC. The parameters of the cavity is listed in Table **3**

The PoP cavity has two large beam pipes with an 84 mm inner diameter as required for LHC, and six small ports perpendicular to the beam axis for the FPC and HOM couplers, Figure 9.

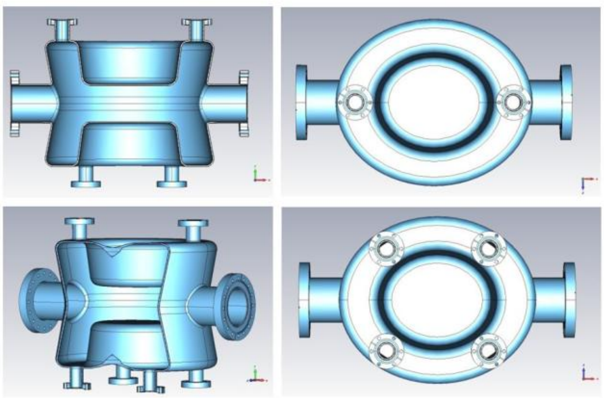

Figure 9: Design of the PoP DQWCC.

Table 3: Parameters of PoP DQWCC

Parameter	Value	Unit
Frequency	400	MHz
First HOM	579	MHz
Cavity Length	384	mm
Cavity width	142	mm
Beam pipe diameter	84	mm
R/Q (accelerator notation)	400	Ohm
Max surface electric field	44	MV/m
Max surface magnetic field	60 (on cavity)	mT

In Figure 10, we plot the R/Q's of HOMs of the PoP cavity up to 2.1 GHz. Since the cavity is not cylindrically symmetric with respect to the beam axis, the HOMs are sorted into several groups according to the orientation of their electric fields at the gap. The resonant frequency of the first HOM, 579 MHz, is largely separated from the fundamental mode, as expected for a quarter wave resonator. Therefore, a high pass filter design can be adapted for the HOM couplers, similar to the 56 MHz cavity discussed above, but simplified by eliminating the sapphires spacers due to much higher frequency of the crab cavity. Study shows that efficient damping can be achieved with only three HOM couplers [16, 17].

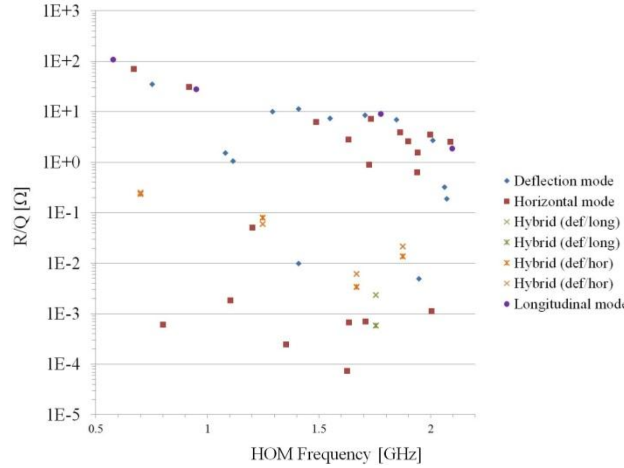

Figure 10: HOM map of PoP DQWCC.

The PoP cavity was fabricated from 4 mm Niobium sheet material, and tested at 4 K and 2 K. The test results are shown in Figure 11 [18]. A multipacting barrier was encountered on at low field, but was easily conditioned. The quality factor of the cavity at low fields is about 3×10^{8}, much lower than expected ($\sim10^{10}$). The Q value did not change after slow cool down, indicating that there is no Q-disease. Also, it was about the same at 2 K and 4.3 K. In CW mode, the highest deflecting voltage V_t we reach is 0.96 MV due to thermal quench. In pulsed mode, we could reach up to 1.34 MV limited by the RF amplifier.

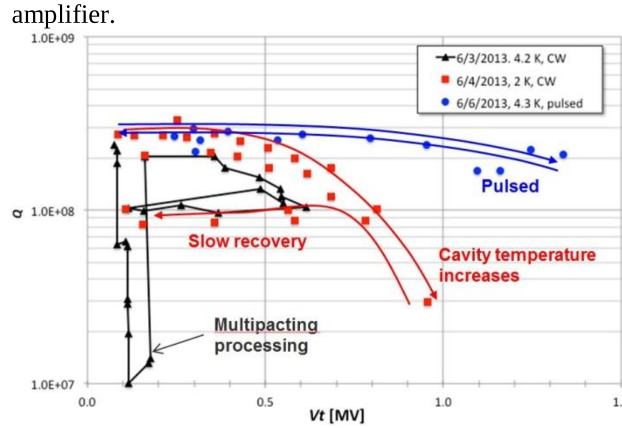

Figure 11: First vertical test result of PoP DQWCC.

During the post testing inspection, stains (possibly chemical residue) were found on the cavity inner surface in the high magnetic field region. These stains will degrade the Nb surface at high fields. Simulations also show that heat dissipation on the couplers and large beam pipe flanges are big contributors to the low Q. Another cold test is being prepared with the cavity re-polished and all couplers and flanges coated with Nb. They should eliminate all the thermal issues and reaching a high Q.

Current Design

The DQWCC design has evolved over the past couple of years to achieve higher gradient, a lower surface field,

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zero on-axis acceleration, and a close-fitting fully enclosed helium vessel [15-17]. The current design is shown in Figure 12 [19].

Six small coupler ports are replaced with four large ports with inner diameter of 62 mm. These ports will be occupied by three HOM couplers and one FPC. The PU will be added to the beam pipe, adjacent to the cavity. The latest design avoided field enhancement at the coupler ports. This design will be used in the cryostat assembly and tested at the Super Proton Synchrotron at CERN with beam.

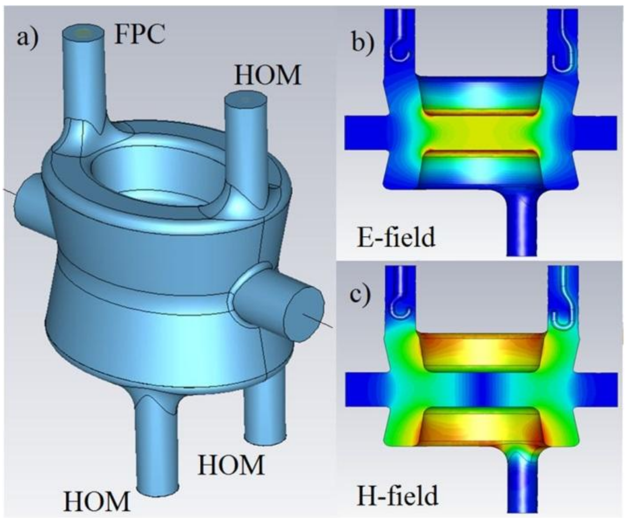

Figure 12: DQWCC current design with FPC and HOM coupler ports (a), and the peak electric field (b) and magnetic field (c).

CONCLUSION

More QWRs are under development in BNL, such as the 84.5 MHz electron gun and booster cavity for Low Energy RHIC electron Cooling (LEReC). These cavities are accelerating units for electrons that are used for ion cooling in the RHIC low energy collision experiments [20].

The QWRs have proved their high standard performance as accelerating cavities in various low energy scenarios [21, 22]. The big advantage in compactness also gained this type of cavities an essential role in hadron colliders. The QWRs make feasible of low frequency and better acceptance RF buckets for long bunch beams, generating electrons with high bunch charge, and providing high gradient deflection.

ACKNOWLEDGMENT

The author would like to thank all who were involved in the work on quarter wave resonator projects at BNL, and their help in providing materials.

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ISBN 978-3-95450-143-4

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