QUARTER WAVE RESONATORS FOR BETA~1 ACCELERATORS *

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Abstract

The Superconducting Quarter Wave Resonator (QWR) was developed first for heavy ion acceleration in 1981 and became highly successful and widespread in low β linacs. Recently the QWR has been adapted for a variety of applications for high particle velocity, near β=1. The applications are varied, from the use in a relativistic hadron storage ring, to photocathode electron guns and crab cavities. In this work I will describe these applications, and how they benefit from the rather unique properties of this resonator, such as the Higher Order Mode spectrum, the electro-mechanical stability and the compact size.

INTRODUCTION

The Quarter Wave Resonator (QWR) is a very basic resonant structure, comprising of the coaxial transmission line shorted at one end, and "open" at the other end, a quarter of the fundamental wavelength from the shorted end. Thus the high impedance at the open end can be used for accelerating particles. The superconducting QWR was developed first for heavy ion acceleration in 1981 [1] and became highly successful and widespread in low β linacs [2].

The QWR has some limitations and some advantages. In applications where the beam travels along the axis of symmetry of the coax line, the resonator is inefficient in using space along the beam line, resulting a low "real-estate" gradient, thus suitable for small number of resonators in situations where space is not of great concern. In applications where the beam travels perpendicular to the axis of symmetry, the real-estate gradient can be quite high. The advantages of the QWR are compactness, extremely high mechanical stability and wide separation of the lowest High Order Mode (HOM) from the fundamental mode.

The most common use of the QWR by far is in the acceleration of low velocity ions, where the QWR has been made in many varieties of materials (lead-plated copper, niobium explosively bonded to copper, pure niobium metal and niobium sputtered on copper), a number of accelerating gaps per cavity and a broad range of particle velocities.

This paper is focused on the use of the QWR in less common applications where the particle velocity is high. In particular I will discuss QWR in use of relativistic heavy ions and electrons and the fast growing application of photocathode RF guns.

RELEVANT PROPERTIES OF THE QWR

The basic QWR is composed of two coaxial conductors, shorted electrically at one end, as shown in Figure 1. Usually, the outer conductor is extended in length beyond the inner conductor, as shown by the dashed

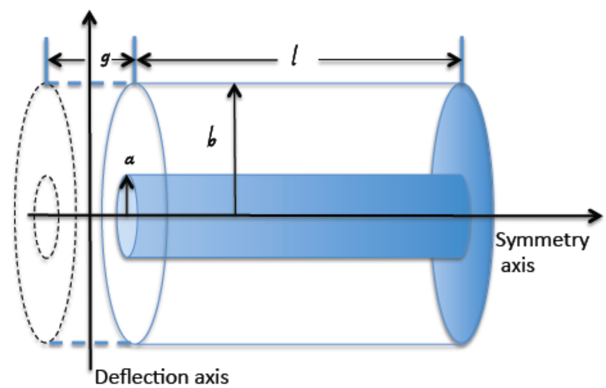

Figure 1: A schematic diagram of a Quarter Wave Resonator, defining its dimensions. The electrically shorted end is to the right.

Electrical Properties

The QWR of length l, radii of the inner and outer conductors a and b, respectively, can be described simply and quite well [1] as a transmission line of characteristic impedance Z_0 terminated by a capacitance C at a length l=λ/4 where λ is the wavelength for the resonant frequency. At resonance, a voltage V is developed between the conductors across the "open" end.

Directing particle beams along a few possible axes can apply this voltage for various purposes. One possibility is along the axis of symmetry, and a few examples will be given for this mode. Another possibility is shown in Figure 1 as the deflection axis, to be used by deflection cavities or crab cavities. The well known axis for low β linacs is paralel to the deflection axis but shifted towards the shorted end, to pass through the inner conductor.

The standing wave causes the voltage to reduce as a cosine function along the conductors, vanishing at the "shorted" end. The magnetic field is described by a sine function, with maximum at the shorted end. Let the surface resistance of the conductor be R_s. The general equation for the impedance of a transmission line is given by

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy..
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$$Z_{in} = Z_0 \frac{Z_l + Z_0 \tanh(\gamma l)}{Z_0 + Z_l \tanh(\gamma l)}$$

Since the line is shorted at its end, Z_l =0, the impedance of the line is

$Z_{in} = Z_0 \tanh(\gamma l)$, and for a coaxial line we have a characteristic impedance Z_0 given by

$$Z_0 = \frac{\eta}{2\pi} \ln \frac{b}{a}$$

η is the impedance of free space. The complex propagation constant is

$$\gamma = \alpha + j\beta$$

with the attenuation coefficient given by

$$\alpha = \frac{R_s}{2\eta} \frac{a^{-1} + b^{-1}}{\ln \frac{b}{a}}$$

where R_s is the surface resistivity on the conductors, ($\eta = \sqrt{\mu / \varepsilon} \sim 377\Omega$), and the propagation constant is

$$\beta = \frac{2\pi}{\lambda}$$

Resonances of the coax line (characterized by diverging Z_{in}) occur at frequencies of of f=c/4l, 3c/4l, 5c/4l… etc. Other modes may show up in a 3-D structure.

At the fundamental resonance of f=c/4l, the (real) shunt resistance is given (in the engineering notation) by

$$R_{sh} = \frac{Z_0}{\alpha l}$$

The unloaded Q and R/Q are given by

$$Q = \frac{\pi}{\alpha\lambda} \qquad R_{sh} / Q = \frac{4Z_0}{\pi}$$

The geometric factor $\Gamma = QR_s$ is given by

$$\Gamma = QR_s = \frac{2\pi\eta}{\lambda} \frac{\ln(b/a)}{a^{-1} + b^{-1}}$$

If there is a capacitor C loading the end of the transmission line, the resonance condition changes such as the length of the transmission line is shorter,

$$\Delta l = \frac{\lambda}{4} - l = cZ_0 C$$

The frequency of the first HOM stays at 3 times the fundamental (for the 1-D transmission line model) even with the capacitive loading. The shunt resistance is reduced by the capacitance

$$R_{sh} = \frac{Z_0}{\alpha l} \frac{1}{\left(\frac{\omega C Z_0}{\alpha l} \right)^2 + 1}$$

The peak surface magnetic field can be estimated in MKS units as

$$H_p = \frac{1}{\eta} \frac{V}{a \ln \frac{b}{a}}$$

or in practical units

$$H_p = \frac{3.3V}{a \ln \frac{b}{a}}$$

where V is in MV, H is in mT, and a in meters.

The peak surface electric field is usually determined by the shaping of the inner conductor. However, it is bounded by the coaxial geometry, which gives

$$E_P \geq \frac{V}{a \cdot \ln(b/a)}$$

HOM Damping

In all the applications that will be discussed here, but most particularly for cavities placed in storage rings, good damping of HOM modes is mandatory. Given the large separation of the fundamental mode from all HOMs, one can use damping loops strongly coupled to the HOMs with high-pass filters to protect the fundamental power from overpowering the HOM load. Figure 2 shows the design of a HOM damping loop designed for the 56MHz RHIC storage cavity [3,4]. The cavity will have four dampers at various locations to couple well to all the HOMs that matter for beam stability.

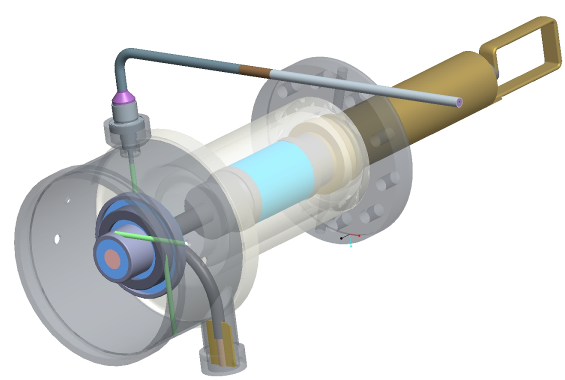

Figure 2: A HOM damper with an integral high-pass filter.

The high-pass filter design of this HOM damper uses the frequency gap between the fundamental mode and the lowest HOM mode to ramp up over 80dB of attenuation of the fundamental mode, while allowing good damping of the HOMs. The filter consists of niobium-sapphire layers forming three capacitors and four line inductors, shown at the left end of the damper assembly. The warm HOM load is connected through the coax line shown at the top of the figure. The cavity vacuum is separated from the cryogenic insulation vacuum by a sapphire window.

Other properties

It is worth mentioning a few other properties of the QWR that are relevant to SRF operations. First, acoustic stability: Due to the symmetry of the electrodes (leading to a zero frequency deviation from motion of the inner conductor relative to the outer conductor in first order), the resonator is intrinsically very stable against mechanical vibrations.

The first mechanical resonant frequency of the niobium QWR center conductor, f, is given approximately by

$$f = 0.28\sqrt{\frac{Ea^2}{\rho l^5}}$$

where E is Young's modulus and ρ is the density. For niobium, E~120 GPa, ρ=8570 kg/m^3. That will place most QWR's center conductor mechanical frequency at over 100 Hz, and this is for low frequency cavities. At high frequency the QWR is much stiffer.

The QWR can also be made very stiff to helium pressure changes. For example, in the BNL 56 MHz QWR has a helium pressure frequency detuning of only 0.3 Hz/mbar. In comparison, a 5-cell 704 MHz elliptical cavity has 26 Hz/mbar. Even if one considers a fractional frequency detuning by pressure, the QWR outperforms the elliptical cavity by almost an order of magnitude. Given that the helium pressure fluctuations are considered the worst detuning mechanism of SRF cavities, this is a significant advantage for the QWR.

Another important property is sensitivity to multipacting. In a very large number of resonators across the world, QWR were found easy to condition through multipacting. For the special applications when multipacting must be avoided altogether, a QWR design that is very resistant to multipacting has been developed [5].

QWR APPLICATIONS

Crab Cavities for eRHIC and LHC

One of the most vexing problems in the design of a deflecting or crab cavity is the damping of various modes such as the Lower Order Mode (LOM, the accelerating mode in an elliptical cavity has a lower frequency than the deflecting cavity), Same Order Mode (SOM, the other polarization of the deflecting mode) and the usual assortment of Higher Order Modes (HOM). The QWR crab cavity [6] has an enormous advantage relative to any other cavity: It has no LOM and no SOM, and the lowest frequency HOM is separated by a large factor (a factor of 3 in the fundamental QWR, but usually less than 3 depending on the exact geometry) whereas elliptical cavities have an HOM as close as 15% to the fundamental. This makes the complex task of damping modes much easier in the QWR.

Making a somewhat crude approximation that the deflection voltage is established by the electric field across the gap g for a distance of 2a (see Figure 1 for definitions), then the QWR crabbing voltage is related to the resonator's voltage by

$$V_{crab} = \frac{\pi a}{g} V$$

This voltage is a limit that is never reached, due to the curvature of the field.

From this expression we also get for the transverse (crabbing) shunt impedance

$$\frac{R_t}{Q} = \left(\frac{\pi a}{g}\right)^2 \frac{R_{sh}}{Q} = \frac{4\pi a^2 Z_0}{g^2}$$

One feature of the QWR as a crab cavity is the acceleration that may be imparted to the beam even in the crabbing phase. While it is possible to design the QWR crab cavity to avoid this acceleration (as will be shown below), a small degree of acceleration (or deceleration) may be easy to accommodate, either by providing the necessary power by the RF system, or even use pair of QWR crab cavities, one which will produce acceleration, the other to produce deceleration (by flipping the cavity 180 degrees about the beam axis) and feed the power from the decelerating cavity to the accelerating cavity and canceling the acceleration for the pair.

LHC: Given that the LHC is operating at the beam-beam limit, an essential component of the luminosity upgrade of the LHC is foreseen as a combination of bunch intensity increase, requiring increased crossing angle, and a reduction of β^{*} with a simultaneous compensation of Piwinski angle using crab cavities [7]. The crab cavities recover the geometrical luminosity loss from increasing crossing angle. They also provide a natural luminosity-leveling knob to maintain a constant luminosity during a physics store and substantially reduce the radiation damage of IR region magnets and detectors.

A number of crab cavity styles have been studied by the LHC Crab Cavity Collaboration. The main challenge in fitting a crab cavity to the LHC is the combination of relatively low frequency (about 400 MHz) and severe size limitations. The size limitation stems from the separation of the LHC beam lines, which is 194 mm center-to-center. This makes a compact cavity essential for the LHC.

A design of a QWR crab cavity for the LHC luminosity upgrade has been made by Rama Calaga [8]. The cavity is shown in Figure 3.

The racetrack design of this cavity makes it extremely compact while retaining a good performance. This cavity has a frequency of 400 MHz, and the nearest other mode is well separated at 675 MHz. Even though it is still un-optimized, it already achieves a transverse voltage of 2.5 MV per cavity with a peak surface magnetic field of 110 mT and peak surface electric field of 48 MV/m, and a transverse shunt impedance Rt/Q of 132 Ohms. However, this design still needs to be optimized to reduce a non-negligible accelerating voltage.

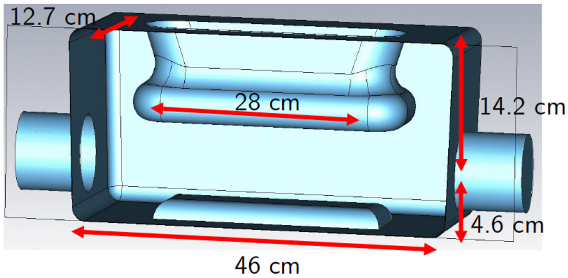

Figure 3: A QWR crab cavity design aimed at the LHC luminosity upgrade.

eRHIC: The half-crossing angle (crabbing angle) designed for eRHIC is 5 mrad, and the hadron bunch length is between 5 to 8 cm, leading to a large crab deflection at 3σ of about 1 mm, or about 200 times larger than the beam size. Thus the challenge for crab cavities at eRHIC is the high linearity required, which requires a combination of low frequency crab cavities with high-harmonic corrections.

An initial design of a crab cavity for eRHIC has been made [9] which eliminates the acceleration produced by the cavity. However, this design is still being optimized at this time. The schematic view of this cavity is shown in Figure 4. The electric parameters of the cavity are given in Table 1. These parameters are excellent, and they demonstrate the inherent advantages of the QWR as a crab cavity. This crab cavity is too large in diameter to yield good estimates using the analytical expressions given above. Figure 5 shows the distribution of the accelerating and deflecting fields along the beam axis. The integrated acceleration of the cavity is nulled to a very high degree by a careful choice of its dimensions. While the price of nulled acceleration is the lowering the characteristic impedance, the performance of this resonator is still excellent in comparison with other choices.

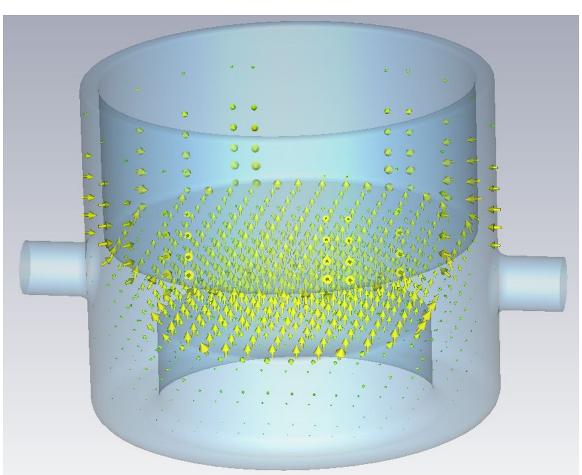

Figure 4: A view of the 181 MHz eRHIC crab cavity showing electric field lines of the fundamental mode.

Table 1: Parameters for an eRHIC crab cavity calculated by Microwave Studio.

QWR crab cavity for RHIC	Units	MWS
Crab mode frequency	MHz	181
Nearest other mode frequency	MHz	251
Length (along beam line)	cm	75.2
Width (long and short parts)	cm	38.1/25.1
Deflecting voltage*	MV	6.1
Peak surface electric field*	MV/m	39
Stored energy*	Joules	100
Rt/Q (Engineering notation)	Ohms	291
Accelerating voltage*	kV	<1

*) for a peak surface magnetic field of 100 mT.

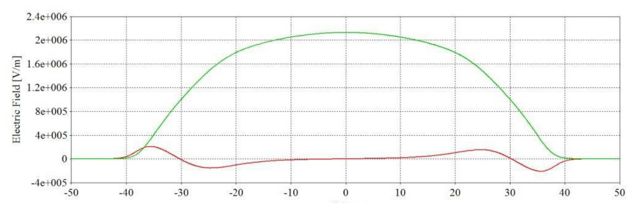

Figure 5: The distribution of the deflecting and accelerating fields in the eRHIC carb cavity. The accelerating field integrated to essentially zero accelerating voltage.

RHIC SRF QWR Cavities

The use of superconducting RF storage cavities for an ion storage ring provides various advantages. In a machine, which injected with a large longitudinal emittance beam, a low frequency but high voltage storage cavity helps to keep the ion bunches in the 'bucket', sometimes eliminating the need for complex bunch gymnastics that may spoil emittance.

Storage Cavity: In RHIC, the use of a superconducting storage cavity at 56 MHz (harmonic 720) allows adiabatic rebucketing directly from the 28 MHz accelerating cavity. Stochastic cooling in RHIC significantly benefits from this new RHIC storage rf system based on superconducting 56 MHz QWR [10]. Such a new storage rf system will benefit all RHIC operations, with and without any cooling, as it eliminates the satellite bunches and therefore reduces the length of the effective vertex distribution, thus leading to a higher effective luminosity.

The SRF storage cavity can be operated as an idler cavity or with very little RF drive, leading to improved reliability and stability. In a machine like RHIC, in which the vacuum is important to battle electron cloud problems, the cryogenic quality vacuum is another advantage. Finally, the large voltage, 2 MV conservatively from single cavity, reduces the part's count and lead to somewhat lower impedance.

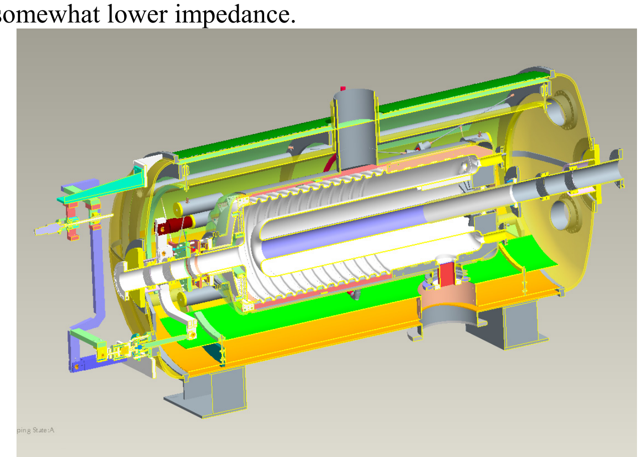

Figure 6: A view of the 56 MHz storage cavity of RHIC.

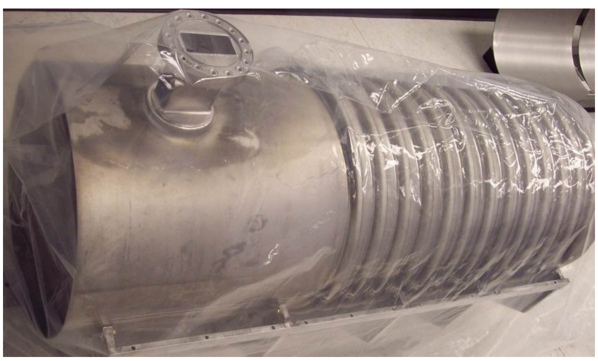

Figure 7: The 56 MHz QWR assembled outer conductor at Niowave.

From Superfish calculation [11], at a voltage of 2.4 MV the 56 MHz QWR has a stored energy of 207 Joules. Assuming a residual resistivity of 10 nOhms, we can expect an unloaded Q of 2×10^9, (geometric factor of 20). At an operating temperature of 4.2 K the BCS surface resistivity is quite a bit smaller than 10 nOhms. Given the r/Q of 40 Ohms, we expect a liquid helium dynamic power load of 41 W. The peak magnetic field is 82 kA/m, and peak electric field 38.9 MV/m, all reasonable numbers. Since the 56 MHz QWR has a shape amenable to the transmission line approximations given above, it is interesting to compare the Superfish calculation to the analytical approximation. The analytical values are: for R/Q 39 Ohms, geometry factor of 19, peak surface magnetic field 100 mT (about 83 kA/m). The peak surface electric field lower limit is 31 MV/m, showing a pretty good geometry optimization to lower the peak field. These approximate values match the numerical results quite well. The match is not this good for the crab cavities whose shapes deviate significantly from the transmission line 1-D model. The SRF guns are somewhere in-between.

It is important for a storage cavity in a synchrotron to be "invisible" to the beam while it is accelerating and the frequency of the beam bunches sweeps past the cavity fundamental mode. For this purpose a "fundamental mode damper" has been developed [12]. When this damper is inserted, the loaded Q of the cavity is extremely low (about 300) making the cavity invisible. The damper is extracted once the beam is at storage energy. The damper is shown in Figure 8 in its fully inserted position.

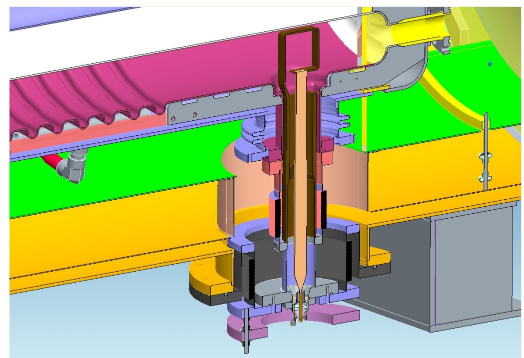

Figure 8: A detail of the fundamental mode damper of the 56 MHz storage cavity of RHIC.

Accelerating Cavity: Accelerating cavities in an ion storage ring require a large tuning range, to track the beam velocity changes. The accelerating structures in the Relativistic Heavy Ion Collider (RHIC) ring are normal-conducting copper structures used to capture the injected beam and accelerate across transition to the final energy, shortening the bunches before they are rebucketed into the storage RF system. Niowave is developing a 28 MHz superconducting accelerating cavity for RHIC, which seeks to replace the four normal-conducting accelerating presently used with two SRF cavities, reducing the RF power requirements and the impact of unwanted higher-order modes, among other advantages.

Table 2: Requirements for RHIC accelerating cavities.

Cavities for RHIC	4
Frequency	28.1 MHz
Gap voltage	600 kV
Tuning range	200 kHz
Tuning rate	22 kHz/s
Aperture	0.1 m

The SRF cavity is an unusual “folded” quarter-wave resonator with a large tuning capacitor. This geometry has not been previously built, and the tuning range (~1 % of the operating frequency) is unprecedented for a superconducting cavity. Furthermore, at 28.1 MHz, this will be the lowest frequency superconducting cavity in operation.

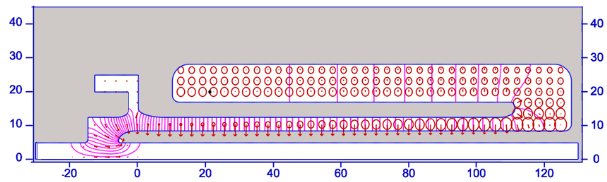

Figure 9: A cross sectional view of the 28 MHz folded QWR for the RHIC accelerating system showing magnetic and electric field lines. The size scale is in cm.

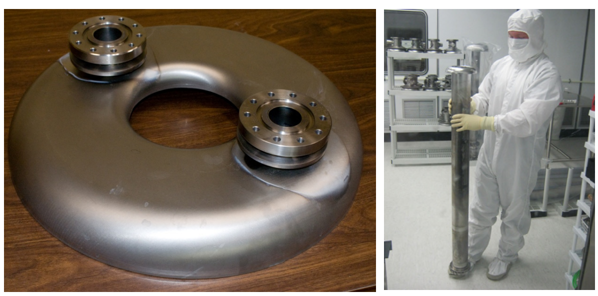

Figure 10: Parts of the 28 MHz accelerating cavity under fabrication at Niowave. Left: the end wall with coupling ports. Right: the beam pipe with nose-cone.

The folded transmission line design feature of this QWR has two advantages: First, it reduces the length of the resonator, simplifying its fabrication and installation. A second advantage is the reduced shunt impedance, which is a good feature in a storage ring where the total impedance of the machine is an issue. The initial design of the cavity by Niowave and BNL leads to a peak surface electric field of 22 MV/m for the design voltage of 650 kV, peak surface magnetic field of 42 mT, a dissipated power at 4.5K of 3.5 W, Q of 1.7×10^9 and R/Q of 71 Ohms.

SRF QWR Laser Photocathode Electron Guns

A review paper on superconducting electron guns is presented in these proceedings [13]. In the following, the QWR superconducting guns are presented in the context of QWR resonator for high β particles.

The application of QWR for SRF photocathode electron guns is spreading rapidly. In many applications, such as free-electrons lasers, electron coolers and colliders, the electron bunch repetition rate is low, certainly under 100 MHz. Beam dynamics considerations for electron guns show that a low frequency is advantageous, since it allows using a larger 3-D volume for the electron bunch. The larger volume is made possible longitudinally by the longer period, which reduces the variation of the RF voltage while the bunch crosses the accelerating gap of the gun. Transversally the volume can be increase with the square of the wavelength due to the reduced transverse variation of the accelerating field across the gap. The large phase space volume (at a given bunch charge) results in a reduction in space-charge forces, the leading emittance growth mechanism. This trend towards a lower frequency will reach a limit when the thermal emittance will become dominant.

Table 3: BNL-U. Wisc.-NPS-Niowave SRF Guns Parameters

Parameter	**Units**	**BNL**	**U. Wi.**	**NPS**
Frequency	MHz	112	200	500
Aperture (beam tube)	cm	10	10	6.35
Cavity Diameter	cm	42	60	24
Cavity Length	cm	110	50.3	20.3
Planned beam energy	MeV	2	4	1.2
Peak electric field	MV/m	38	53	51
Peak magnetic field	mT	73	80.4	78
Peak / cathode field	-	2.63	1.31	1.8
QR_s (geometry factor)	Ω	38	85	125
R/Q (linac definition)	Ω	126	147	195
Q_0 (no cathode, 4.5K)	$\times 10^9$	3.7	3.3	1.2

For low frequency applications, the QWR offers great advantages of compactness, stability and good electrical performance, in particular the well-separated and sparse HOM spectrum. Two laboratories have worked with Niowave, Inc. to build and test QWR SRF guns, NPS [14] and BNL [15]. A third laboratory, University of Wisconsin, placed an order for the construction of such a gun, to be built also by Niowave [16].

The parameters of the three guns are given in Table 3. The Q values quoted in Table 3 assume a residual surface resistance of 5 nΩ. The NPS gun at the highest frequency of 500 MHz is still dominated by the BCS surface resistivity, whereas the BNL gun, at the lowest frequency of the three guns, has a contribution from residual resistivity larger than BCS surface resistance.

500MHz gun (Niowave / NPS):

The Naval Postgraduate School (NPS) in Monterey, CA and Niowave designed and built this QWR SRF gun as a development program of high-quality beam injectors. They recently reported [14] initial results from the 500 MHz superconducting radio-frequency electron gun, the first SRF QWR device to be built and tested. In initial operation, the gun has generated beams with bunch charge in excess of 78 pC, energy of 469 keV, and normalized rms emittances of about 4.9 µm. In that initial test, the bunch charge was limited by the available drive laser energy, and the beam energy was limited by x-ray production and the available rf power. No fundamental limits on beam charge or energy have been encountered, and no high-field quenching events have been observed.

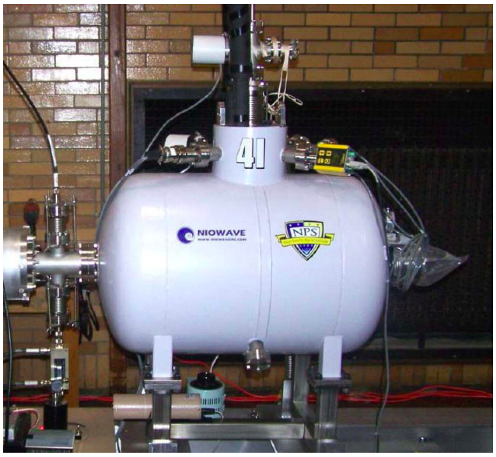

Figure 11: The fully assembled NPS/Niowave 500 MHz gun.

The design of this relatively high frequency QWR resonator has a number of innovative features, such as the stepped cathode insert (for reduced RF losses) and the interchangeable cathode tip insert, as seen in Figure 11. The cathode insert has also RF pick-up probes.

The measured quality factor of the cavity as a function of the integrated beam voltage for two consecutive tests are shown in Figure 12. Helium processing nearly tripled the achieved voltage levels.

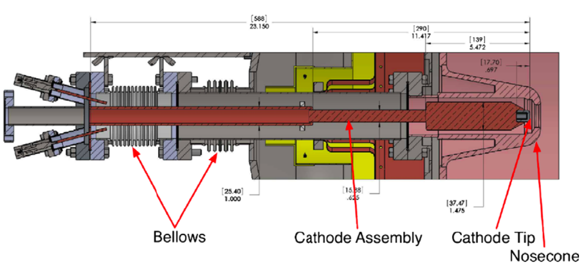

Figure 12: The cathode assembly of the NPS/Niowave gun, with a stepped center conductor and interchangeable cathode tip.

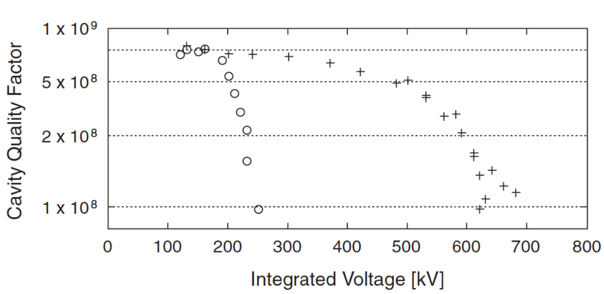

Figure 13: Measured quality factor as a function of integrated voltage in two tests of the NPS/Niowave gun.

112MHz gun (Niowave / BNL):

The 112MHz gun has been developed under a SBIR grant from DOE NP to Niowave, aimed at developing a gun to produce a high quality electron beam for an electron cooling program of the RHIC machine at BNL. The gun has been built and initial testing has been done [13], [17] and it will be used for a proof-of-principle demonstration of Coherent electron Cooling (CeC) [18]. In This application the gun will be essentially driving a single-pass high-gain FEL amplifier, but this amplifier is used to amplify a charge imprint of ions of the RHIC beam to be used then to cool the ions. Another application of this gun is the development of high-quantum efficiency photocathodes, in a program funded by DOE BES at Stony Brook University, BNL and LBNL. It has the lowest frequency of the three guns reported here.

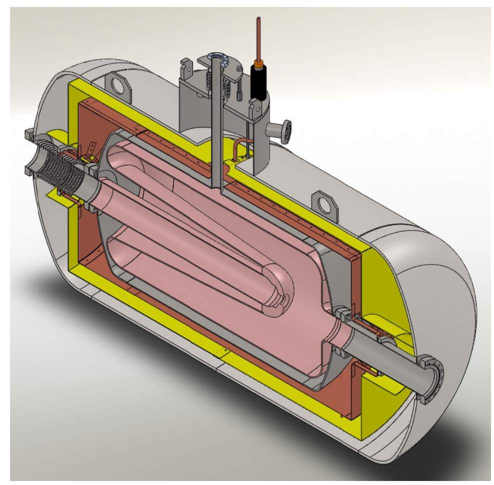

Figure 14: Cutout view of the BNL/Niowave 112 MHz gun.

A schematic drawing of the cavity assembly is shown in Figure 14, and the completed gun is shown in Figure 15. The results of the initial test of the cavity, limited by radiation safety protocol to very low fields, is shown in Figure 16.

Figure 15: The assembled BNL/Niowave 112 MHz gun.

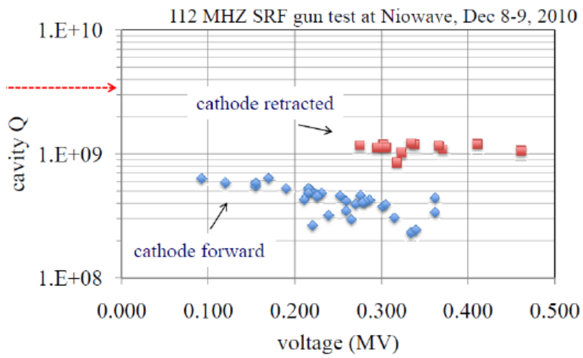

Figure 16: Measured quality factor vs. integrated voltage in the first test of the BNL/Niowave 112 MHz gun.

200 MHz gun (Niowave / Wisconsin)

The University of Wisconsin-Madison/Synchrotron Radiation Center is advancing its design for a seeded VUV/soft X-ray Free Electron Laser facility called WiFEL. To support this vision of an ultimate light source, they are pursuing a program of strategic R&D addressing several crucial elements [16]. This includes development of a high repetition rate, VHF superconducting RF electron gun. At this time, the gun shown in Figure 17 is being fabricated at Niowave with testing beginning next year.

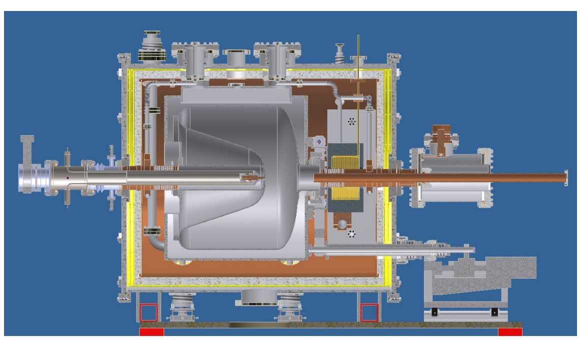

Figure 17: The design for the UW/Niowave 200 MHz gun.

SUMMARY

Superconducting Quarter Wave Resonators have been traditionally used in low velocity ion accelerators. Recently we see a wealth of new applications for the ubiquitous QWR at particle velocities approaching light, where new properties, like the HOM spectrum of the QWR, become important. This report described some fundamental properties of the QWR and various applications in storage rings and electron guns.

REFERENCES

[1] I. Ben-Zvi and J.M. Brennan, "The Quarter Wave Resonator as a Superconducting Linac Element", Nuclear Instruments and Methods in Physics Research **A212**, 73 (1983).

[2] G. Bisoffi, "Review of Low Beta Structures", IEEE Transactions on Applied Superconductivity, **9**, 285 (1999).

[3] Q. Wu and I. Ben-Zvi, "Simulations of the High-Pass Filter for the 56 MHz Cavity for RHIC", Proceeding of IPAC'10, Kyoto, Japan, ISBN 978-92-9083-352-9.

[4] Q. Wu and I. Ben-Zvi, "Optimization of Higher Order Mode Dampers in the 56 MHz SRF Cavity for RHIC", Proceedings of IPAC'10, Kyoto, Japan, ISBN 978-92-9083-352-9.

[5] D. Naik and I. Ben-Zvi, "Suppressing Multipacting in a 56 MHz Quarter Wave Resonator", Physical Review Special Topics - Accelerators and Beams **13**, 052001 (2010).

[6] I. Ben-Zvi, "The Quarter Wave Resonator as a Crabbing Cavity", LHC-CC10, 4th LHC Crab Cavity Workshop, 15-16 December 2010 CERN, Geneva Switzerland.

[7] R. Calaga, R. Tomas, F. Zimmermann, "LHC Crab Cavity Aspects and Strategy", TUOAMH02, Proceedings of IPAC'10, Kyoto, Japan, ISBN 978-92-9083-352-9.

[8] R. Calaga, Proceedings of this conference, 2011 SRF Conference, FRIOB05.

[9] Q. Wu, S. Belomestnykh, I. Ben-Zvi, Proceedings of this conference THPO007.

[10] I. Ben-Zvi, "Superconducting Storage Cavity for RHIC", Collider-Accelerator Department Accelerator Physics Notes, BNL, C-A/AP/337 January 2009.

[11] X. Chang, I. Ben-Zvi, "Geometric Optimization of the 56MHz SRF Cavity and its Frequency Table", Collider-Accelerator Department Accelerator Physics Notes, BNL,C-A/AP/331 October 2008.

[12] Q. Wu, S. Bellavia, I. Ben-Zvi, M. Grau, G. Miglionico, C. Pai, "Fundamental Damper Power Calculation of the 56MHz SRF Cavity For RHIC", Proceedings of 2011 Particle Accelerator Conference, New York, NY, USA, March 28-April1, 2011.

[13] S. Belomestnykh, Proceedings of this conference MOIOB04.

[14] J. R. Harris, K. L. Ferguson, J.W. Lewellen, S. P. Niles, B. Rusnak, R. L. Swent, and W. B. Colson, T. I. Smith, C. H. Boulware, T. L. Grimm, P. R. Cunningham, M. S. Curtin, D. C. Miccolis, D. J. Sox and W. S. Graves, "Design and Operation of a Superconducting Quarter-wave Electron Gun", Physical Review Special Topics - Accelerators and Beams **14**, 053501 (2011).

[15] S. Belomestnykh, I. Ben-Zvi1, C.H. Boulware, X. Chang, T.L. Grimm, B. Siegel, R. Than, M. Winowski, "Design and First Cold Test of BNL Superconducting 112 MHz QWR for Electron Gun Applications", Proceedings PAC11, March 28-April 1, New York, NY, USA.

[16] J. Bisognano, R. Bosch, D. Eisert, M. Fisher, M. Green, K. Jacobs, K. Kleman, J. Kulpin, G. Rogers, J. Lawler, D. Yavuz, R.Legg, T. Miller, "Progress Toward the Wisconsin Free Electron Laser",

Proceedings PAC11, March 28-April 1, New York, NY, USA.
[17] S. Belomestnykh, Proceedings of this conference, MOPO054.
[18] V.N. Litvinenko et al., "Proof-of-Principle Experiment for FEL-Based Coherent Electron Cooling", Proceedings of 2011 Particle Accelerator Conference, New York, NY, USA, March 28-April1, 2011. THOBN3.