DESIGN OF A SUPERCONDUCTING QUARTER-WAVE RESONATOR FOR eRHIC *

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Abstract

The electron-ion collider project (eRHIC) at Brookhaven National Laboratory requires a 50 mA 12 MeV electron injector for the eRHIC main linac [1] and an SRF electron gun for a Coherent electron Cooling (CeC) linac [2]. The necessity to deal with long electron bunches required for both the eRHIC injector and the coherent electron cooler sets the frequency requirement of 84.5 MHz. A quarter wave resonator is an obvious choice for this frequency because of its dimensions, RF parameters and good experience with manufacturing and using them at ANL. Here we present the design and optimization of an 84.5 MHz superconducting quarter-wave cavity with accelerating voltage of 2.5 MV suitable for both machines. One QWR will be used as a bunching cavity in the injector linac, the other one as the photoemission electron source for the CeC linac. In addition to the optimization of the QWR electromagnetic design we will discuss the tuner design, approaches to cavity fabrication and processing.

INTRODUCTION

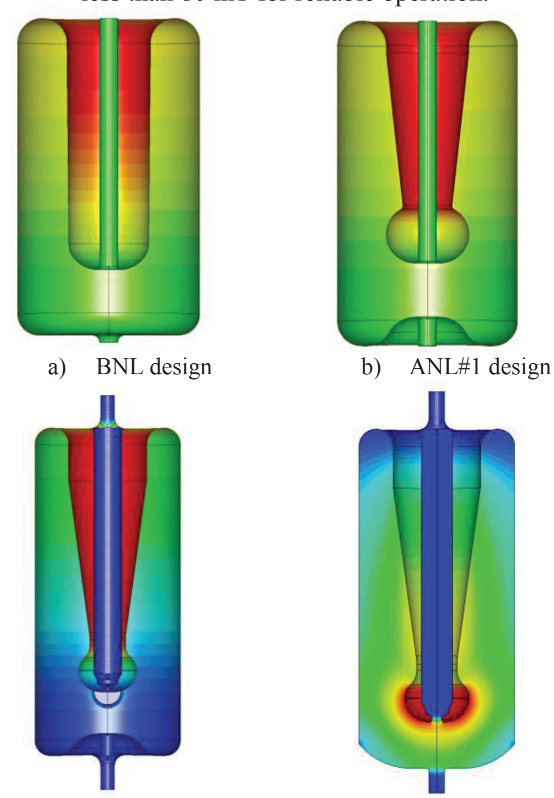
Both eRHIC injector and CeC linac have similar requirements for the front-end: they need to accelerate electron beams up to ultra-relativistic velocities (2.5 to 12 MeV), operate with a bunched beam, and require to provide beam transport of the electron bunches without significant degradation of beam emittance and energy spread [3]. These requirements limit the RF frequency of the cavities to 84.5 MHz in order to provide relatively long bunches. The other important requirement for the electron cooling linac is the capability to tune its frequency over a 78 kHz range in order to synchronize it with the heavy ion beam revolution frequency of RHIC.

One of the most efficient cavity types for such low frequencies are superconducting Quarter-Wave Resonators (QWRs) that are widely used in $\beta \sim 0.1$ part of ion linacs. Argonne National Laboratory has significant experience in building such cavities for ATLAS Upgrade Program [4], so QWRs would be a natural choice for this application because of the dimensions and highly-optimized RF parameters. Changing from a 2-gap layout to 1-gap eliminates the problem of velocity acceptance which otherwise becomes a problem for ultra-relativistic electron beams.

ELECTROMAGNETIC DESIGN

The electromagnetic design was done in CST Microwave Studio [5]. The following considerations were taken into account for the cavity design and shape optimization:

- An operating frequency of 84.85 MHz QWR to accelerate electrons in a longitudinal gap;
- A diameter of the cavity not to exceed 65 cm to fit into BNL's vertical test facility;
- 2.5 MV accelerating voltage with a peak electric field less than 40 MV/m and magnetic field less than 80 mT for reliable operation.



a) BNL design b) ANL#1 design c) ANL#2 design d) ANL#3 design

Figure 1: Cavity electromagnetic design progress (electromagnetic field distribution)

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As a starting point for the cavity design we have used an ATLAS QWR [4] and a preliminary design of BNL LEReC QWRs [6] as shown in Figure 1a. Then, several modifications were applied in order to improve the RF parameters as shown in Fig. 1b: The conical shape of the stem helped to distribute surface magnetic field equally and reduce surface losses. Optimizing the top diameter of inner conductor where the H-field is concentrated has also resulted in an R/Q increase. The smaller inner conductor diameter near the electric field region also reduces parasitic capacitance between walls and inner conductor. Another important design improvement is the introduction of the re-entrant nose at the bottom of the cavity, which helped concentrate the electric field near the beam axis and thus increased the shunt impedance.

The next design shown in Figure 1c introduced the following changes. The inner conductor geometry was modified in order to reduce peak fields. A straight section was introduced and the taper angle was increased. This allowed an increase in the gap between the inner and outer conductors in the electric field region while keeping the electrode surface almost the same in the magnetic field region.

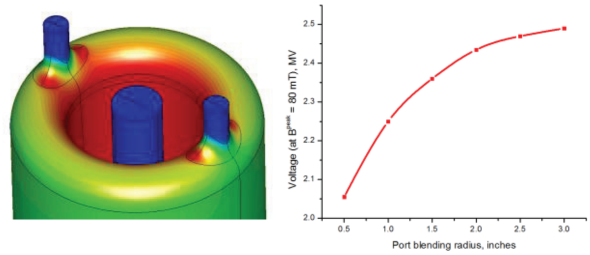
We have considered the elimination of the spherical shape of the inner conductor tip that would simplify the manufacturing and avoid the formation of helium bubbles that could be trapped in this region in horizontal operation of the cavity. But since this problem isn't of much concern when operating at 2K, we have decided to keep and further optimize the shape of the spherical-like inner conductor tip. The optimum shape has a smaller diameter of the inner conductor, which reduces the parasitic capacitance. On the other hand, it has a large area in the high electric field region, which reduces the peak fields.

Further modification attempts were made in order to improve the cavity performance. Making a round bottom shape increases the capacitance and can potentially increase the tuning sensitivity. But apparently, it results in RF parameters deterioration and doesn't help substantially in frequency tuning as the "beam-axis" capacitance remains the same.

Table 1: Final design RF cavity parameters

Design	BNL	ANL#1	ANL#2	ANL#3
Voltage, MV	2.5	2.5	2.5	2.5
R/Q, Ω	108.6	162.2	168.8	160.2
B_{peak}, mT	81.0	81.0	60.4	80.3
E_{peak}, MV/m	38.9	38.5	39.5	39.2

A comparison of RF parameters of different cavity designs is summarized in Table 1. These values include the magnetic field increase at the port-to-cavity junctions as seen in Figure 2a. This peak field can be reduced significantly by increasing the port blending radius up to ~4.6 cm as demonstrated in Fig. 2b. Further radius increases don't reduce the magnetic field as it starts to concentrate near the toroid and cylinder junction.



a) Magnetic field distribution near ports

b) Cavity voltage as a function of port blending radius

Figure 2: Local magnetic field on the port connection to the cavity

MECHANICAL DESIGN

The mechanical design and structural analysis of the niobium cavity was done using ANSYS Multiphysics [7] and included several stages (as shown in Figure 3) in order to reduce *df/dp* by increasing the overall rigidity or by compensating deformations in the electric field region by increasing the deformations in the magnetic field region and vice versa:

a) A top niobium plate was added
b) A doubler plate was added
c) Bottom gussets were added
d) A bottom titanium plate was added

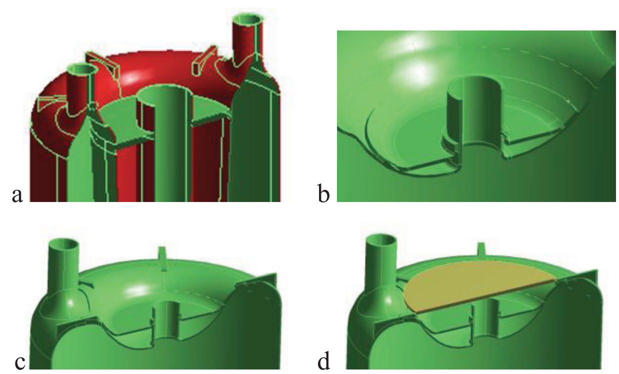


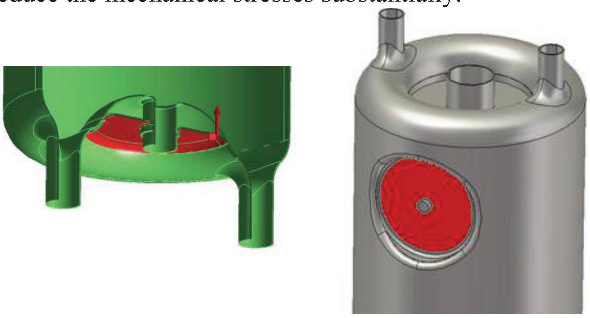
Figure 3: Mechanical design steps as listed in the paper

As one can see from this list, the bottom part, where the electric field is dominant, was strengthened, while the magnetic field region was relaxed. These modifications allowed a reduction of *df/dp* down to -14.9 Hz/mbar.

SLOW TUNER

The most challenging part of the cavity design is a slow tuner which should provide a tuning range of 78 kHz for the 84.5 MHz operating frequency. The first approach to design a slow tuner was to squeeze the cavity longitudinally. This will interact with the high electric field region and should provide effective tuning. Since this cavity is planned to be used as an SRF-gun, the inner conductor should remain fixed and we propose to push the bottom doubler plate as shown in Figure 4a. The required force can be applied using pneumatic tuners similar to those used for Argonne QWRs [8].

The simulation results (see Table 2) predict that the required deformation of 3 mm in this area causes very high mechanical stresses and increases *df/dp* dramatically. Though, it is possible to reduce *df/dp* and even cancel it by introducing flat areas in the magnetic field region (similar to those, shown in Fig. 4b), it is difficult to reduce the mechanical stresses substantially.



a) Electric region b) Magnetic region

Figure 4: Slow tuner mechanisms (red – deformation area)

One way to increase the mobility of the bottom side of the cavity is to insert a bellows section in the niobium to make it movable. However, the simulation results (Fig. 5) predicted that enormous deformations are required to achieve the 78 kHz tuning range and thus much higher stresses and force values. Such an option was dismissed.

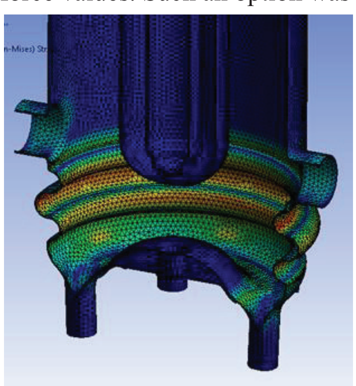


Figure 5: Von Mises stresses distribution for bellows tuner

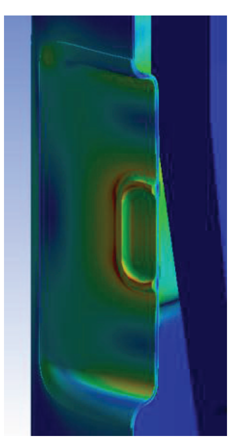


Figure 6: Von Mises stresses distribution for magnetic region tuner

The other option of resonant frequency adjustment is to push in the magnetic field region. The most efficient way to do this is to make a flat area in the top region of the outside conductor and apply a force. Although, intensive optimization of the tuner that included the flat region and reinforcing ring shapes, thicknesses, dimensions, number and location, improved all the parameters of the magnetic field tuner compared to the electric region tuner, we were not able to reduce the mechanical stresses around the reinforcing rings completely. Figure 5 shows the von Mises stresses distribution near the area where the force was applied. Although, the peak stress values (red) are high, they are located on the surface and don't penetrate inside the niobium and thus are tolerable.

Table 2: Slow tuner performance

Type	Electric	Bellows	Magnetic
df/dp, Hz/mbar	-41.6	-56.3	-8.9
df/dN, Hz/N	-4.15	+0.8	+9.4
Required Force, kN	18.8	101.3	8.3
Max deformations, mm	3.0	11.8	2.6
Max stresses, MPa	282	600	180

SUMMARY

A one-gap 84.5 MHz QWR cavity capable of accelerating electrons by 2.5 MV was developed and could be used in the electron injector linac for eRHIC or as an SRF electron gun for a CeC linac. The cavity shape was thoroughly optimized in order to reduce peak electric and magnetic fields to 40 MV/m and 60 mT. The mechanical design of the cavity was done to reduce *df/dp* values and allow for a 78 kHz slow tuning range. Several types of tuning technologies including pushing on electric or magnetic field regions and introducing cavity bellows were studied and the most promising results were obtained when introducing four rectangular shape flats near the magnetic field region.

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