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RF AND MECHANICAL DESIGN OF A 915 MHz SRF CAVITY FOR CONDUCTION-COOLED CRYOMODULES *

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Abstract

Conduction-cooled SRF niobium cavities are being developed for use in compact, continuous-wave electron linear accelerators for a variety of industrial applications. A 915 MHz two-cell cavity has been designed to achieve an energy gain of 3.5 MeV. The design of the cell shape aims at minimizing the peak surface magnetic field. Field flatness is achieved by adjusting the length of the outer end half-cells. The higher-order mode analysis shows that absorbers are not required for a moderate beam current of 5 mA. One of the beam tubes has two side-ports for insertion of coaxial fundamental power couplers. The mechanical design and analysis were done to maintain a stress near or less than 15.5 MPa for all anticipated loading conditions. This is half the measured yield strength and is to provide relief from creep when the cavity is evacuated and stored with outside atmospheric pressure.

INTRODUCTION

Superconducting radio-frequency (SRF) cavities are commonly used in modern particle accelerators to increase the energy of a charged-particle beam. R&D projects in the last few years have demonstrated the possibility to operate SRF cavities cooled by commercial cryocoolers at an accelerating gradient of up to ~12 MV/m [1, 2].

These results may allow envisioning compact, high-power, continuous-wave electron accelerators with energy of up to 10 MeV for industrial irradiation applications, such as wastewater treatment, medical device sterilization and phytosanitary treatment [3, 4]. The beam power of these possible novel accelerators has to be greater than hundreds of kilowatt, ideally up to 1 MW, to reduce the unit cost of treatment. Given the high beam power requirements, the RF source of the accelerator has to have a high efficiency to reduce the operating cost of the accelerator. Commercially available 915 MHz industrial magnetrons have an electrical efficiency of ~90% with an output power of ~100 kW. An ongoing R&D project at Jefferson Lab and General Atomics is targeting to demonstration of efficient power combining from multiple magnetrons and developing the control system to drive an SRF cavity [5].

In this contribution we present the RF design and the mechanical analysis of a 915 MHz two-cell cavity as part of a larger R&D project aiming at developing a conduction-cooled cryomodule, which includes cryocoolers, a coaxial fundamental power coupler (FPC) and warm-to-cold beamline transitions. The number of cells was determined by the available cryocoolers and space within a vacuum vessel developed for a preceding project. Details about the FPC design, done by RadiaBeam, can be found in Ref. [6].

RF DESIGN

The cavity was designed aiming to provide an energy gain of at least 3.5 MeV to a relativistic electron beam. SUPERFISH [7] was used for the electromagnetic design of the cell shape. The shape design aimed at reducing the ratio of the peak surface magnetic field, B_p, to the accelerating gradient, E_{acc}, while maintaining a wall angle, α, that facilitates surface chemical and cleaning processes. The iris radius, R_{iris} was chosen to be close to the largest possible value that could fit within the beamline flange used in 1.3 GHz TESLA-type cavities, allowing the use of testing hardware already available. The cell shape design includes a short straight segment, L_{eq}, that is used as a parameter to tune the frequency of the end half-cell. This allows using a single die for pressing both center and end half-cells. Furthermore, the presence of a straight section at the equator facilitates electron-beam welding of a Nb ring for conduction cooling. The equator radius, R_{eq}, was used as a parameter to tune frequency of the center half-cell. Table 1 lists the geometric parameters of the center half-cell. The equator weld-prep is included in the cell-shape design and an arc with 2 mm radius is used to connect the straight section at the equator to the equator ellipse's arc. The end half-cell is identical to the center half-cell other than L_{eq} = 3.1 mm.

The list of electromagnetic parameters of the 2-cell cavity is given in Table 2. The highest B_p measured on a conduction-cooled Nb_3Sn-coated cavity was 50 mT, which would correspond to E_{acc} = 13.6 MV/m and an energy gain of 4.3 MeV for this cavity shape.

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Table 1: Geometric Parameters of the Center Half-Cell

Parameter	Value
R_{iris}	45 mm
Length	81.9 mm
Equator ellipse semi-major axis	58.5 mm
Equator ellipse semi-minor axis	45 mm
L_{eq}	8 mm
R_{eq}	140.14 mm
α	6°
Iris ellipse semi-major axis	15.75 mm
Iris ellipse semi-minor axis	11.5 mm

Table 2: Electromagnetic Parameters of the 915 MHz 2-Cell Cavity

Parameter	Value
E_p/E_{acc}	2.17
B_p/E_{acc}	3.69 mT/(MV/m)
R/Q	264.0 Ω
G	275 Ω

Multipacting (MP) analysis was done with FishPact [8] and the results are summarized in Fig. 1, showing a plot of the final energy of a secondary electron after 20 impacts as a function of E_{acc}, for different values of the secondary electron's initial energy. Considering a threshold energy for the secondary emission yield (SEY) to be > 1 of 25 eV, no MP is predicted up to ~13 MV/m. The MP trajectories correspond to a 1st-order, 2-point MP across the equator. Another way to estimate the proneness of a cell shape to MP is to calculate the "p-value" from the radial and axial electric field components close to the equator [9]. The "p-value" for our cell shape design is 0.225, lower than the threshold value of ~0.28 for cell shapes with strong MP.

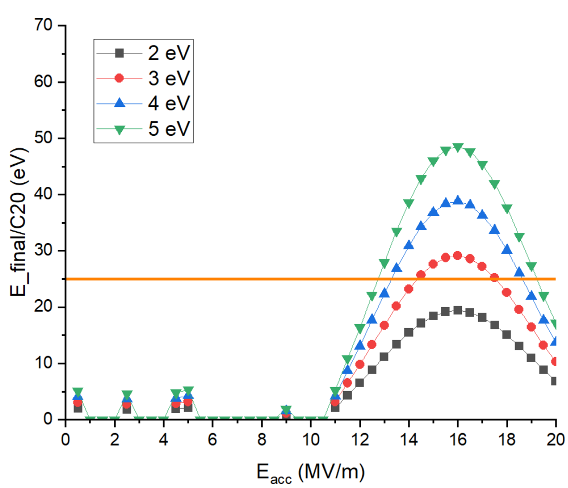

Figure 1: Final impact energy of secondary electron after 20 impacts as a function of E_{acc} for different values of the electron's initial energy. The orange line is the estimated threshold for SEY > 1.

CST Studio Suite [10] was used to determine the location of the FPC on the beam tube and the higher-order mode (HOM) analysis. The dimensions of the inner and outer conductors of the FPC are the same as those of the FPC used for the SNS cavities [11] and the distance between the center of the inner conductor and the iris of the end half-cell was determined to be 64 mm, in order to achieve $Q_{ext} = 3 \times 10^6$ with the tip of the antenna flush with the beam tube.

The longitudinal and transverse impedance of the HOMs were computed by lossy eigenmode simulations. A beam current of 5 mA, an initial beam energy of 600 keV, a bunch charge of 5.5 pC and a longitudinal rms beam size of 16.7 mm were considered as beam parameters to determine the impact of the HOMs. The analysis was carried out with a similar method to that described in Ref. [3] and the results showed that the power dissipation due to monopole modes is ~14.5 mW and the transverse deviation angle from all dipole modes is ~3 μrad. Therefore HOM absorbers would not be needed if the cavity were to be used in an accelerator with the beam parameters which were taken into consideration.

MECHANICAL ANALYSIS

The cavity is intended to be fabricated using 4 mm thick high-purity Nb sheets. The cavity flanges are to be made of Ti45Nb and stainless steel caps cover the flanges. After fabrication and standard surface treatments, the inner surface of the cavity will be coated with Nb_3Sn layer at 1200 °C for 6 h in a vacuum furnace. This process will reduce the yield strength of Nb to ~31 MPa (4.5 ksi) [12]. Past experience showed that the Nb_3Sn layer can be easily damaged as a result of a plastic deformation of the Nb substrate [2, 13]. There was a case where such plastic deformation occurred after a 1 atm pressure differential was applied to a 952 MHz single-cell cavity over a period of several months [2]. The mechanical design and analysis of the cavity using the finite-element software Ansys [14] was carried out with the objective of achieving a maximum von Mises stress at the inner cavity surface to be ≤15.5 MPa, which is half of the yield strength of Nb annealed at 1200 °C for 6 h, under any of the following load conditions:

1. The cavity is held horizontal, "simply supported" at the beamline flanges, subjected to gravity and 1 atm pressure differential. This represents the case of the cavity being handled under vacuum.
2. The cavity is held vertically at a beamline flange, subjected to gravity and 1.56 atm pressure differential. This is the relief pressure of the vertical cryostat used for SRF cavity testing at Jefferson Lab.
3. The cavity is held horizontal, "simply supported" at the beamline flanges, subjected to gravity and the weight of the acid mixture used for electropolishing, filling 60% of its volume.
4. The cavity is held horizontal, with fixed supports on the beamtubes, subjected to gravity, 1 atm pressure differential and the following shock accelerations, applied independently: 4g in the vertical direction, 1.5g in the

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lateral direction and 5g along the beamline. This represents the case of the cavity being shipped under vacuum.

The Nb material parameters used for the analysis are: Young's modulus = 103.4 GPa, yield strength = 31 MPa, ultimate tensile strength = 89.6 MPa and Poisson's ratio = 0.38, density = 8.58 g/cm^3. The analysis is set up with bi-linear elastic-perfectly plastic material properties with a specified yield strength and small displacement theory. As a results of the analysis, gussets needed to be added between the beam tubes and the cooling plates to meet the design criteria for load case No. 2. Stiffening rings between the cells and the beam-tube cooling plates at 180 mm inner diameter have also been added. Figure 2 shows a 3D model of the cavity.

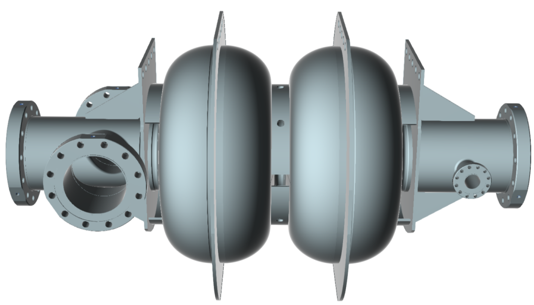

Figure 2: 3D model of the 915 MHz 2-cell cavity.

Table 3 shows the maximum stress on the cavity inner surface for each load condition and Fig. 3 shows the stress distribution for load case No. 2. Further mechanical analysis has been done with respect to protection against local failure, buckling and failure from cyclic loading. With respect to protection against plastic collapse, the limit load was found to be 2.35 atm, which is a factor 1.5 greater than the maximum allowable working pressure. The results showed that the cavity meets the requirements of the American Society of Mechanical Engineers (ASME) pressure vessel code [15].

Table 3: Maximum von Mises stress, σ_M, at the inner surface of the 915 MHz 2-cell cavity for different load conditions. "H" = horizontal, "V" = vertical.

Load condition	σ_M **(MPa)**
H, gravity, 1 atm diff.	9.1
V, gravity, 1.56 atm diff.	12.9
H, gravity, 187 N V	1.5
H, 1 atm diff., 4g V	10.6
H, gravity, 1 atm diff., 1.5g lateral	10.8
H, gravity, 1 atm diff., 5g H	12.9

The cavity axial stiffness and tuning sensitivity were computed to be 24.4 kN/mm and 677 kHz/mm, respectively. A modal analysis was carried out for the unconstrained cavity to compute the frequency of the first 21 non-zero modes. The frequencies of the lowest four modes are: 136.3 Hz, 230.7 Hz, 245.6 Hz and 356.6 Hz. Given that the lowest

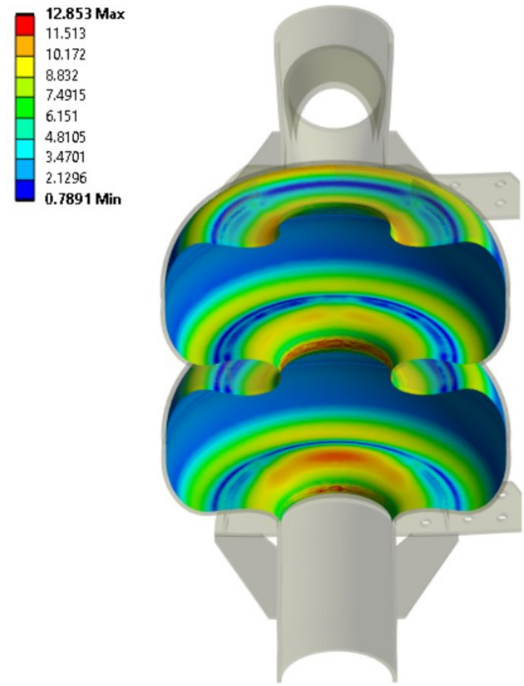

Figure 3: Von Mises stress distribution in the cells of the 2-cell cavity held vertical by the top flange and subjected to gravity and 1.56 atm. The values in the color map are in MPa. A scaling factor was used to highlight the deformation.

frequency is above 120 Hz, the cavity should be relatively insensitive to microphonics.

CONCLUSION

The cell shape for a 915 MHz cavity has been designed to allow reaching a design accelerating gradient of 11 MV/m with a peak surface magnetic field of less than 50 mT and no MP barrier predicted below this gradient. A straight section at the equator was an added feature that allows using a single die to fabricate the cavity and facilitates the welding of a cooling ring at the equator.

The mechanical design and analysis of the cavity was done aiming at the peak stress at the inner surface to be less than 15.5 MPa, in order to avoid any potential plastic deformation under different load conditions. The cavity as designed meets the ASME pressure vessel code. Detailed thermal analysis of the cavity have also been done and the results will be reported in future publications.

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