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HIGHER ORDER MODE ANALYSIS OF A 915 MHz 2-CELL CAVITY FOR A PROTOTYPE INDUSTRIAL ACCELERATOR

A. Castilla*, G. Ciovati, J. Guo, G.-T. Park, R. Rimmer, J. Vennekate
Thomas Jefferson National Accelerator Facility, Newport News, VA, USA

Abstract

A possible solution to reduce the complexity posed by the cryogenic systems in a superconducting RF accelerator for industrial applications, is to capitalize on the advances achieved by the Nb_3Sn superconducting RF technology, as well as the feasibility of a reliable 4 K cooling system, based on commercial cryocoolers. Following this philosophy, the conceptual design for a prototype, conduction-cooled, 4 MeV, 20 kW SRF electron linac, is being developed at Jefferson Lab. Such design is based on a 915 MHz 2-cell Nb_3Sn cavity. In this contribution, we present the proposed cavity design, including the fundamental power coupler, and the preliminary analysis of the Higher Order Modes, using numerical simulations to estimate the potentially dangerous modes as a starting point to evaluate the requirements for damping for reliable operations with a cryocooler. Finally, different methods to calculate the Higher Order Modes' Impedances are briefly discussed.

INTRODUCTION

Recent advances in high-performance superconducting Nb_3Sn-coated superconducting radio-frequency cavities and commercial 4 K cryocoolers enabled the development of prototype SRF cavities operating at accelerating gradients up to ~12 MV/m, without the use of a liquid helium bath.

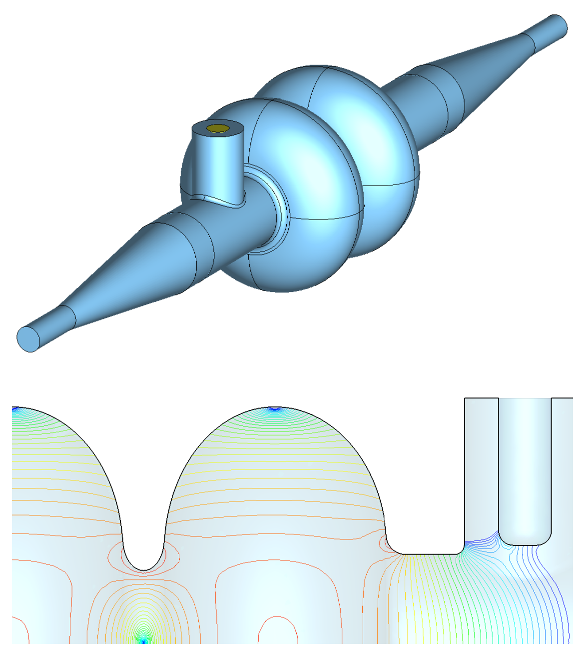
Such developments could facilitate transitioning the efficient SRF technology for use in industrial accelerators. One possible applications is for environmental remediation such as the treatment of wastewater and flue gases, requiring an electron beam energy of ≤10 MeV but a high beam power, up to ~1 MW. The conceptual design for such type of accelerator, based on a 650 MHz 5-cell cavity, can be found in [1]. Jefferson Lab is developing the design for a similar type of accelerator [2], based on a 915 MHz 5-cell cavity, Low-cost, high efficiency, high-power magnetrons for industrial heating are commercially available at 915 MHz and using such devices as the accelerator's high-power RF source would lower both its capital and operating cost.

Most of the technical solutions related to the development of a compact, efficient, conduction-cooled SRF linac could be demonstrated in a demo accelerator, aiming at 4 MeV, 20 kW. Such an accelerator may represent a short path towards producing a working prototype that could attract the interest of potential users of the technology.

* acastill@jlab.org

2-CELL CAVITY DESIGN

A 915 MHz 2-cell cavity has been designed to accelerate a 600 keV electron beam up to 4 MeV. The geometry of the 2-cell cavity is the same as that of the end-cells of the 5-cell cavity described in [3]. The cell length is 163.8 mm, the beam tube diameter is 110 mm, the diameter of the iris between the two cells is 90 mm and the equator diameter is 293.6 mm. To facilitate the interfacing of the demonstrator's module, a reduction in the beam pipe to 1.5 inches is proposed (similar to the CEBAF's C100 modules, see Fig. 1(a)). This modification increases the flange-to-flange length to approximately 1.5 m and results in a cutoff frequency of around 4.6 GHz for the TM_{010} mode. This option can be revisited if it is deemed to introduce too many complications, an alternative could be to extend the 90 mm and place beam line absorbers (BLAs) in the warm section, prior to the beam pipe reduction. A fundamental power coupler (FPC) has been adapted from Oak Ridge's PPU design [4] to have a $Q_{ext} \approx 3.5 \times 10^6$ (see Fig. 1(b)). For a summary of the main parameters, refer to Table 1.



(a)

(b)

Figure 1: Schematic of the 2-cell cavity vacuum volume, including the FPC and beam-pipe tapers (a) and the equipotential lines of the operational mode including the FPC (b).

HOM CALCULATIONS

As part of the HOM analysis campaign, a comparison was conducted between two different methods of calculating HOM impedances using CST eigenmode solvers. The first

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Table 1: Summary of the 2-cell Cavity Design Parameters

Parameter	Value	Units
Flange-to-flange length	1.55	m
Cavity radius	146.8	mm
Iris radius	45.0	mm
Smallest pipe radius	19.1	mm
Resonant frequency (f_0)	914.8	MHz
Shunt impedance (R_{sh})	8.14	MΩ
R/Q	229.5	Ω
External quality factor (Q_{ext})	4.5×10^6	–
Peak surface magnetic field (B_p^*)	4.08	mT
Peak surface electric field (E_p^*)	2.20	mT
On axis $E_{acc,max}$ @4 MV	23.5	MV/m

* normalized to E_{acc} = 1 MV/m

method, described in detail in [5, 6], utilizes ideal absorbers and the default (perturbative) eigenmode solver (Fig. 2(a)). This method has demonstrated excellent results when compared to impedances obtained from wakefield analysis and other techniques, across various cavity types and frequencies. However, it has the drawback of generating numerous spurious modes, attributed to the presence of the "fake" idealized material with relatively high dielectric constant. Consequently, the analysis becomes time-consuming and cumbersome, requiring manual identification and selection of modes by RF experts.

In recent versions of CST, a lossy (general) eigenmode solver has been implemented, offering support for open boundary conditions (Fig. 2(b)). This solver ensures minimal spurious reflections at the ports and beampipes, while eliminating the need for high dielectric constant "fake" materials. As a result, the process of analyzing HOMs is significantly simplified. In our comparison, both methods yielded consistent results for the first 50 modes, once the spurious modes are disregarded.

Higher Order Modes in the cavity can present a significant risk to its stable operation. In this context, a partial analysis of the HOM longitudinal and transverse impedances is presented in Figs. 3(a) and (b) respectively. These impedance analyses provide valuable insights into the distribution and behavior of HOMs within the cavity structure. Through the examination of the impedance spectra, we can identify the dominant HOMs and their corresponding frequencies, which aids in determining the optimal damping approach to ensure reliable cavity operation with a cryocooler.

From Figs. 3(a) and (b), it is evident that the inclusion of additional modes (between 3.4 and 4.6 GHz) is necessary to conduct a comprehensive study of the potentially hazardous modes. This aspect is currently a work in progress. Furthermore, Fig. 3(b) demonstrates that some modes already exceed the single pass BBU threshold. Notably, the modes with vertical polarization exhibit slightly lower impedances compared to those with horizontal polarization. This difference arises due to the placement of the FPC at the top of the beampipe, resulting in improved coupling to the vertical

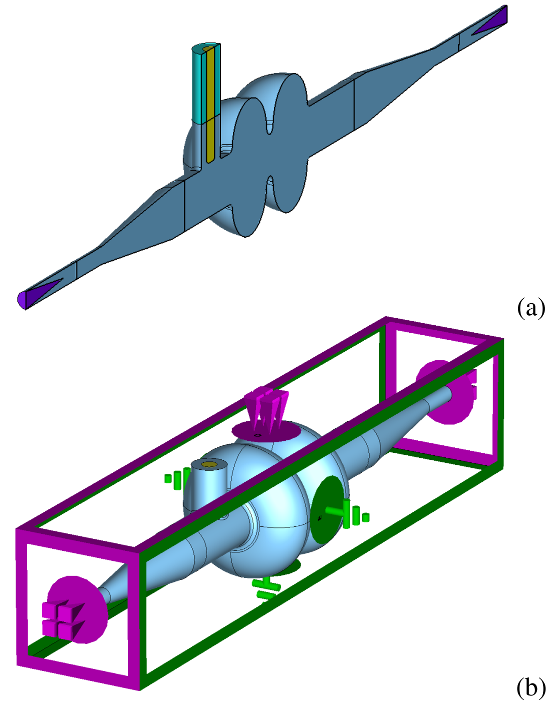

Figure 2: Cavity cross section showing the ideal absorbers used in the general eigenmode solver (a) and the open boundary conditions (in magenta) used in the lossy eigenmode solver (b).

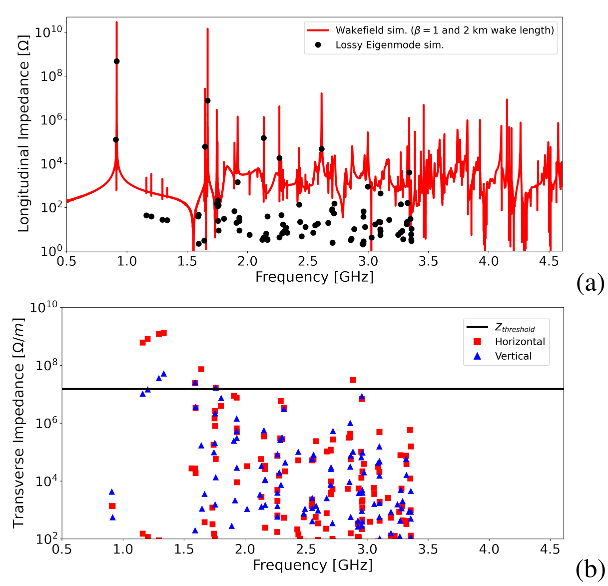

Figure 3: Monopole modes impedances using the lossy eigenmode and the wakefield simulations in CST (a) dipole modes impedances against the single pass Beam Break-Up (BBU) threshold (b).

modes. In light of these findings, it is evident that a damping mechanism must be designed and implemented to mitigate the effects of these transverse modes. Regarding the longitudinal modes, a total loss factor of $k_{||}$ = 0.526 V/pC was calculated. Utilizing the parameters described in Table 2, we estimate a negligible total power dissipation of 14.5 mW.

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Table 2: Beam Parameters for the CW-SC Linac

Parameter	Value	Units
Initial energy	600	keV
Final energy	4	MeV
Beam power	20	kW
Beam current	5	mA
Bunch charge	5.5	pC
σ_{rms}	16.7	mm

It is crucial to emphasize that both the eigenmode and wakefield simulations were conducted without assuming any symmetries. This approach guarantees that no specific modes, which possess genuine characteristics beyond those of monopoles or dipoles, are inadvertently disregarded or excluded. Moreover, the calculation of the longitudinal, vertical, and horizontal R/Q values is performed for each individual mode. This comprehensive analysis accounts for the possibility of hybrid modes or the presence of dipole components arising from symmetry breaking induced by the Fundamental Power Coupler (FPC).

The described method may appear straightforward and logical, as it inherently is. However, further refinements are necessary to enhance the overall efficiency of the entire process, as it currently demands substantial computational time. Additionally, the method should be benchmarked with diverse cavity configurations to ensure its effectiveness across various scenarios. The authors' primary objective is to stimulate a discourse within the community, encouraging the exploration of more efficient approaches for conducting similar analyses.

CONCLUSION & PROSPECTS

The comparison between two different methods of calculating HOM impedances demonstrated consistent results, with both methods yielding similar outcomes for the first 50 modes. The lossy eigenmode solver with open boundaries in CST proved to be an efficient approach for analyzing HOMs, simplifying the analysis process by eliminating the need for ideal absorbing materials and the spurious modes associated to them.

The analysis of Higher Order Modes (HOMs) in the cavity revealed the presence of potentially dangerous modes that require further investigation. The impedance spectra provided valuable insights into the distribution and behavior of HOMs, aiding in the determination of optimal damping approaches. The preliminary analysis indicated that additional modes need to be included between 3.4 and 4.6 GHz to conduct a comprehensive study of the potentially hazardous modes. Moreover, it was observed that some modes already exceed the single pass Beam Break-Up (BBU) threshold. The modes with vertical polarization exhibited slightly lower impedances compared to those with horizontal polarization due to the FPC's placement on the top of the beampipe. To ensure reliable cavity operation with a cryocooler, a damping mechanism will need to be designed and implemented for these transverse modes.

For the longitudinal modes, a total loss factor of $k_{||}$ = 0.526 V/pC was calculated, resulting in a negligible total power dissipation of 14.5 mW eliminating the need for a dedicated beam line absorbers.

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REFERENCES

[1] R. C. Dhuley *et al.*, "Design of a 10 MeV, 1000 kW average power electron-beam accelerator for wastewater treatment applications", *Phys. Rev. Spec. Top. Accel. Beams*, vol. 25, 2022. doi:10.1103/PhysRevAccelBeams.25.041601

[2] G. Ciovati *et al.*, "Design of a cw, low-energy, high-power superconducting linac for environmental applications", *Phys. Rev. Accel. Beams*, vol. 21, no. 9, p. 091601, 2018. doi:10.1103/PhysRevAccelBeams.21.091601

[3] J. Vennekate *et al.*, "On the Way to a 10 MeV, Conduction-Cooled, Compact SRF Accelerator", presented at SRF'23, Grand Rapids, MI, USA, Jun. 2023, paper TUPTB033, this conference.

[4] K.M. Wilson *et al.*, "The Prototype Fundamental Power Coupler for the Spallation Neutron Source Superconducting Cavities Design and Initial Test Results", in *Proc. SRF'01*, Tsukuba, Japan, Sep. 2001, paper PT021, pp. 535–539. https://jacow.org/srf01/papers/PT021.pdf

[5] F. Marhauser, R. A. Rimmer, K. Tian, and H. Wang, "Enhanced Method for Cavity Impedance Calculations", in *Proc. PAC'09*, Vancover, DC, Canada, 2015, pp. 4523-4525.

[6] F. Marhauser, "Calculations for RF cavities with Dissipative Material", in *Proc. SRF2015*, Whistler, BC, Canada, Sep. 2015, pp. 1056–1060. doi:10.18429/JACoW-SRF2015-THPB003