ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-THPOJ021

HIGHER ORDER MODES INVESTIGATION IN THE PERLE SUPERCONDUCTING RF CAVITY

C. Barbagallo*[1], P. Duchesne, W. Kaabi, G. Olry, F. Zomer[1]
Laboratoire de Physique des 2 Infinis Irène Joliot-Curie (IJCLab), Orsay, France
R. A. Rimmer, H. Wang, Jefferson Lab, Newport News, VA 23606, USA
[1]also at The Paris-Saclay University, Gif-sur-Yvette, France

Abstract

The regenerative Beam Break Up (BBU) excited by the dipole Higher Order Modes (HOMs) in superconducting RF (SRF) cavities is a crucial issue for continuous-wave high-current energy recovery linacs. Beam-induced monopole HOMs can increase the cryogenic losses of the linac also. One of the ways to limit these effects is to use HOM couplers on the beam tubes of cavities to absorb and untrap cavity eigenmodes. These couplers feature antennas designed to damp dangerous HOMs and adequately reject the fundamental mode. This study illustrates an investigation of the HOMs of a 5-cell 801.58 MHz elliptical SRF cavity designed for PERLE (Powerful Energy Recovery Linac for Experiments), a multi-turn energy recovery linac (ERL) currently under study and later to be hosted at IJCLab in Orsay. Time-domain wakefield and frequency-domain eigenmode simulations have been used to calculate the cavity broadband HOM impedance spectra and identify the dangerous BBU HOMs. The transmission characteristics of several coaxial HOM couplers have been studied. The efficiencies of several HOM-damping schemes have been compared to propose a HOM endgroup to be fabricated and added to the existing bare SRF cavity.

INTRODUCTION

PERLE [1] is a novel ERL focusing on the generation of high-current electron test beams in CW (continuous-wave) mode for a broad range of particle accelerator applications. For high-current ERL, a relevant effect is multi-pass BBU which emerges when the electron beam interacts with the Higher Order Modes of the accelerating cavity [2], giving rise to beam instabilities and increasing the cryogenic load. To mitigate this phenomenon, the next generation of ERLs, such as PERLE, calls for using SRF cavities with strong HOM-damping requirements [3].

This paper presents an HOMs investigation, carried out in CST Studio Suite [4], for the 5-cell 801.58 MHz bare-cavity design proposed for PERLE by Jefferson Lab (JLab) [1]. Several coaxial HOM couplers are optimized based on the HOM spectrum of the cavity to extract the energy of the most dangerous HOMs. In addition, HOM-damped cavities are compared in terms of beam impedance, and suitable HOM-damping schemes aimed to satisfy PERLE's BBU requirements are proposed.

* carmelo.barbagallo@ijclab.in2p3.fr

PERLE OVERVIEW

The PERLE accelerator complex, shown in Fig. 1, consists of a racetrack topology featuring two parallel superconducting linacs, each containing an 82 MeV cryomodule hosting four 801.58 MHz 5-cell elliptical Nb cavities. Three vertically stacked recirculating arcs on each side complete the accelerator configuration.

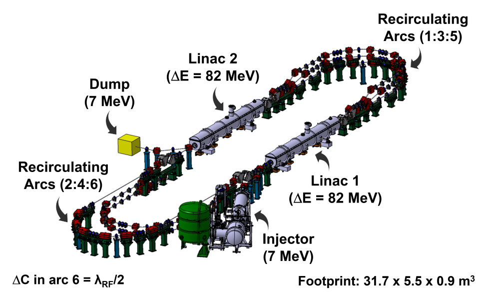


Figure 1: The PERLE accelerator complex layout.

Before entering the machine, a pre-accelerating unit following the source accelerates the electron beam up to the injection energy of 7 MeV. The 20 mA electron beam is boosted in energy by each of the two 82 MeV cryomodules. Hence, in three re-circulation passes, the target beam energy of approximately 500 MeV is achieved [5]. To allow operation in energy recovery mode, after the acceleration, the beam is phase shifted by 180° to be decelerated in three consecutive passes. Consequently, in the deceleration phase, the beam energy is transferred back to the SRF system, and the final beam is directed to a beam dump at its initial energy [1].

SRF CAVITY DESIGN

The first 5-cell 801.58 MHz Nb bare cavity suitable for PERLE has already been designed, fabricated, and successfully tested at JLab in 2018. The cavity design (Fig. 2) features a rather large cell-to-cell coupling (k_{cc} = 2.93 %) to cope with HOM-damping needs, while keeping the ratios of the surface peak electric field E_{pk}, and surface peak magnetic field, B_{pk}, to the accelerating field, E_{acc}, small to pursue a high accelerating gradient (E_{pk}/E_{acc} = 2.38, B_{pk}/E_{acc} = 4.62 mT/MV/m) [6]. The geometric shunt impedance of the cavity is R/Q = 524.25 Ω.

Higher Order Modes

For high-current ERLs, identifying and damping potentially dangerous HOMs is crucial for the beam stability and

ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-THPOJO21

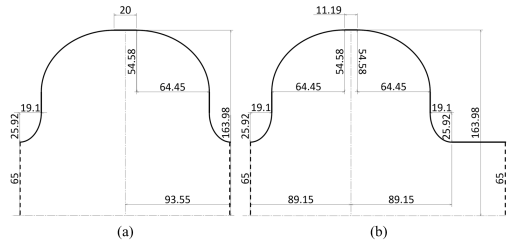


Figure 2: Middle-cell (a) and end-cell (b) design of the optimized 5-cell PERLE cavity. Unit is in mm.

refrigeration requirements of SRF linacs. Typically, the most problematic parasite modes are the first two dipole modes (TE_{111} and TM_{110}) and the first monopole mode (TM_{011}), which usually reside below the corresponding beam tube cut-off and possess high R/Q values. The longitudinal, $(R/Q)_{\parallel}$, and transverse shunt impedance, $(R/Q)_{\perp}$, are calculated, respectively, via:

$$\left(\frac{R}{Q}\right)_{\parallel} = \frac{V^2_{\parallel(r=0)}}{\omega U} \quad (\Omega)\,, \tag{1}$$

$$\left(\frac{R}{Q}\right)_{\perp} = \frac{\left(V_{\parallel(r=r_0)} - V_{\parallel(r=0)}\right)^2}{k r_0^2 \omega U} \quad (\Omega\ \mathrm{m}^{-1})\,, \tag{2}$$

where $k = \omega/c$ is the wave number, r_0 the radial beam offset from the cavity axis, $V_{\parallel(r=r_0)}$ the transit-time corrected voltage along the cavity, and U the cavity stored energy. Figure 3 shows the HOMs with significant R/Q values for the 5-cell PERLE cavity. The TM_{012} π-mode appears at around 2.25 GHz and remains confined within the cavity mid-cells. From Eq. (1) and Eq. (2), the longitudinal, $R_{\parallel} = (R/Q)_{\parallel} \cdot Q_l$, and transverse impedance, $R_{\perp} = (R/Q)_{\perp} \cdot Q_l$, can be derived, where Q_l is the loaded quality factor. Since RF losses in superconducting cavities can be neglected, it is assumed that $Q_l \approx Q_{ext}$, where Q_{ext} is the external quality factor, which relates the HOM-damping by the coupler. Modes with high R/Q values require low Q_{ext} values and vice versa. To provide beam stability, the impedance of the most dangerous mode has to be reduced below the impedance instability thresholds ($Z_{\parallel}^{th}$ for monopole modes and $Z_{\perp}^{th}$ for dipole modes), which can be computed via BBU analyses for an ERL [7, 8].

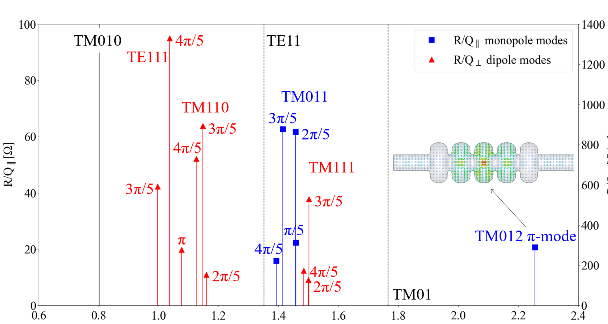


Figure 3: HOMs with the highest R/Q-values computed up to 2.4 GHz in the 5-cell bare cavity.

HOM COUPLERS

The primary goal of seeking a suitable HOM-damping scheme consists in optimizing the HOM-coupler RF transmission according to the HOM spectrum of the cavity (Fig. 3). In the following, the probe and hook-type coupler design [9], and a rescaled version of the DQW coupler [10], are selected for our investigation (Fig. 4).

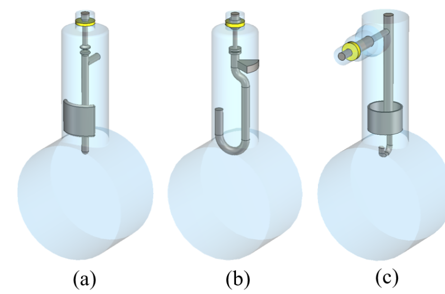


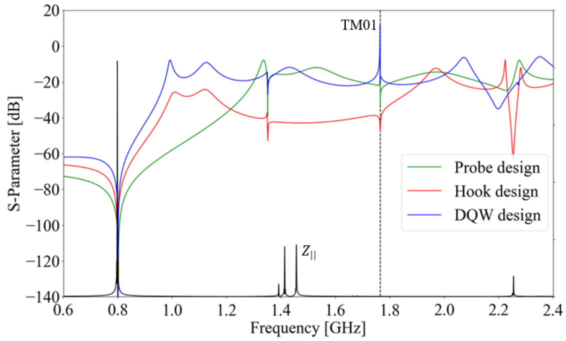
Figure 4: Examples of HOM coupler designs: a) probe coupler, b) hook coupler, c) DQW coupler.

HOM couplers are optimized using the 3D frequency domain solver of CST [4]. The goal is to obtain high transmission at frequencies where HOMs with a high level of impedance exist in the cavity without compromising the fundamental mode efficiency. As a first optimization attempt, a transmission higher than -15 dB and -10 dB is aimed for the worst monopole and dipole HOMs, respectively. Only the coupler connected to the beam pipe is considered to reduce CPU time. Beam pipe ends are terminated with waveguide ports, allowing the excitation of monopole and dipole modes, whereas the TEM mode is damped at the coaxial output of the coupler. The S-parameters between each excitation mode at the beam pipe port, simulating the field pattern inside the cavity, and the port at the coaxial output of the coupler are studied. Particularly, the TM_{01}-TEM transmission describes monopole coupling, whereas the TE_{11}-TEM transmission describes dipole coupling. A penetration depth of 20 mm into the cutoff tube is chosen for the coupling antenna of the three couplers. The results for the optimized couplers are illustrated in Fig. 5. The hook coupler provides higher damping of the first two dipole passbands, while the DQW coupler exhibits a better monopole coupling for modes around 1.43 GHz than the probe design. The main advantage of the DQW design is its ability to provide good damping of both the first monopole and dipole passbands. Otherwise, a combination of the probe-type and hook-type coupler is needed for monopole and dipole damping. However, a higher transmission might be needed according to BBU requirements.

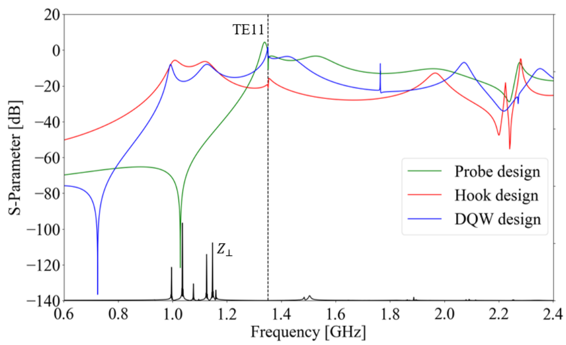
IMPEDANCE SPECTRUM

The broadband coupling impedance spectra have been computed using the 3D wakefield solver of CST [4]. The longitudinal wake potential is calculated considering a single bunch of Gaussian shape traversing the cavity axis. Two electron bunches with an opposite charge and equal offsets

ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-THPOJ021



(a)



(b)

Figure 5: S_{21} of the HOM couplers: a) TM_{01}-TEM transmission, b) TE_{11}-TEM transmission for the most convenient dipole polarization.

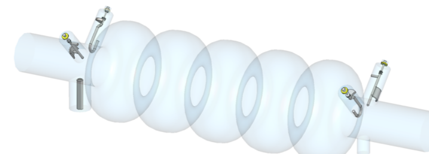
from the beam axis are used to simulate the dipole excitation [11]. Then, the impedance spectrum is derived using a customized FFT [12] of the wake potential in both longitudinal and transversal directions [13]:

$$Z_{\|}(\mathbf{r},\omega) = \frac{1}{c}\int_{-\infty}^{\infty} w_{\|}(\mathbf{r},s)\mathrm{e}^{-\frac{j\omega s}{c}}\,\mathrm{d}s \quad (\Omega), \tag{3}$$

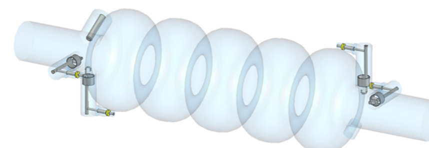
$$\mathbf{Z}_{\perp}(\mathbf{r},\omega) = \frac{c}{\omega r_0}\nabla_{\perp} Z_{\|}(\mathbf{r},\omega) \quad (\Omega\ \mathrm{m}^{-1}), \tag{4}$$

where $w_{\|}$ is the longitudinal wake potential. Herein, the transverse impedance at a certain r_0 radial beam offset from the cavity axis is computed according to the Panofsky-Wenzel theorem. Two damping schemes are compared in this paper as shown in Fig. 6. The first scheme comprises two hook-type and two probe-type couplers (2H2P scheme). In the second scenario, four DQW couplers (4DQW scheme) are employed. HOM couplers are terminated with waveguide ports, while open-condition is applied to the beam pipe ends. Figure 7 shows the longitudinal and transverse impedance spectrum of the cavity for the analyzed damping schemes.

Results show that the employed 4DQW scheme can capture the trapped monopole (TM_{011}, TM_{020}) and dipole (TE_{111}, TM_{110}) modes more efficiently than the 2H2P scheme. The impedance of the rather confined TM_{012} π-mode is independent of the damping scheme as it resonates significantly above the TM01 beam tube cut-off. Yet, further geometrical optimization of the end-cell shape may significantly improve the coupling to the TM_{012} π-mode.

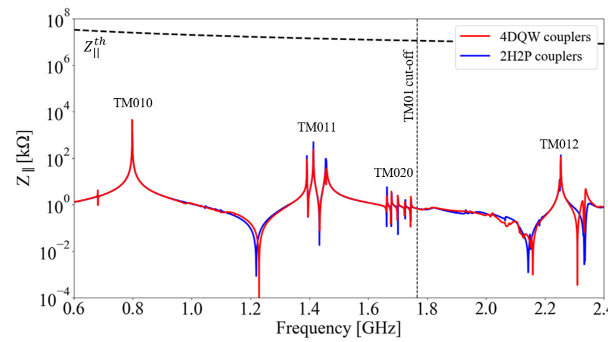


(a)

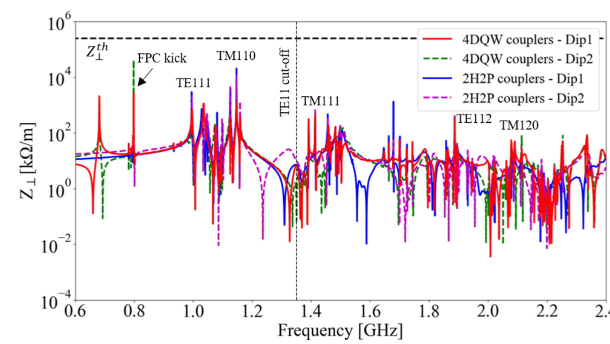


(b)

Figure 6: a) 2H2P and b) 4DQW HOM-damping scheme.



(a)



(b)

Figure 7: Longitudinal (a) and transverse (b) impedance of the cavity for the analyzed damping schemes. The wake impedance is extrapolated from a wake length of 500 m.

CONCLUSION

In this paper, the HOMs of a 5-cell 801.58 MHz cavity designed for PERLE were analyzed. Dangerous modes with high R/Q-values were identified up to 2.4 GHz. Three different HOM-coupler designs (probe, hook, DQW coupler) were optimized based on the HOM spectrum of the cavity. Two different HOM damping schemes were compared (2H2P and 4DQW scheme). Results show that the hook coupler and the DQW coupler provide higher damping for the confined dipole and monopole HOMs, respectively. The damping scheme with four DQW couplers showed promising results in damping both monopole and dipole HOMs below the stability limit. Further aspects, such as the evaluation of HOM power, need to be studied to decide on a final end-group design for the PERLE cavity.

ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-THPOJ021

REFERENCES

[1] D. Angal-Kalinin *et al.*, "PERLE. Powerful energy recovery linac for experiments. Conceptual design report", *Journal of Physics G: Nuclear and Particle Physics*, vol. 45, no. 6, p. 065003, 2018. doi:10.1088/1361-6471/aaa171

[2] S. A. Bogacz *et al.*, "PERLE - Lattice Design and Beam Dynamics Studies", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 4556–4559. doi:10.18429/JACoW-IPAC2018-THPMK105

[3] F. Marhauser, "Next generation Hom-damping", *Supercond. Sci. Technol.*, vol. 30, no. 6, p. 063002, 2017. doi:10.1088/1361-6668/aa6b8d

[4] CST Studio Suite 2021, https://www.cst.com/.

[5] W. Kaabi *et al.*, "PERLE: A High Power Energy Recovery Facility", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 1396–1399. doi:10.18429/JACoW-IPAC2019-TUPGW008

[6] F. Marhauser *et al.*, "Recent results on a multi-cell 802 MHz bulk Nb cavity", presented at the *FCC week 2018*, Amsterdam, Netherlands, 2018. https://indico.cern.ch/event/656491/contributions/2932251/attachments/1629681/2597650/5_cell_Cavity_Marhauser.pdf

[7] C. Song *et al.*, "Longitudinal BBU Threshold Current in Recirculating Linacs", *Tech. Rep.*, Cornell-ERL-06-04, 2006.

[8] R. Kazimi *et al.*, "Observation and Mitigation of Multipass BBU in CEBAF", in *Proc. EPAC'08*, Genoa, Italy, Jun. 2008, paper WEPP087, pp. 2722–2724.

[9] P. Sotirios, "Higher Order Mode Couplers Optimization for the 800 MHz Harmonic System for HL-LHC. HL-LHC (High Luminosity - Large Hadron Collider)", CERN-STUDENTS-Note-2014-114, CERN, Geneva, Switzerland, Aug. 2014.

[10] J. A. Mitchell, G. Burt, R. Calaga, S. Verdu-Andres, and B. P. Xiao, "DQW HOM Coupler Design for the HL-LHC", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 3663–3666. doi:10.18429/JACoW-IPAC2018-THPAL018

[11] H. Wang, F. Marhauser, and R. A. Rimmer, "Simulation and Measurements of a Heavily HOM-Damped Multi-cell SRF Cavity Prototype", in *Proc. PAC'07*, Albuquerque, NM, USA, Jun. 2007, paper WEPMS070, pp. 2496–2498.

[12] F. Marhauser, R. A. Rimmer, K. Tian, and H. Wang, "Enhanced Method for Cavity Impedance Calculations", in *Proc. PAC'09*, Vancouver, Canada, May 2009, paper FR5PFP094, pp. 4523–4525.

[13] L. Palumbo *et al.*, "Wake fields and impedance", *arXiv preprint physics/0309023*, 2003.