HIGHER ORDER MODES INVESTIGATION IN THE PERLE SUPERCONDUCTING RF CAVITY

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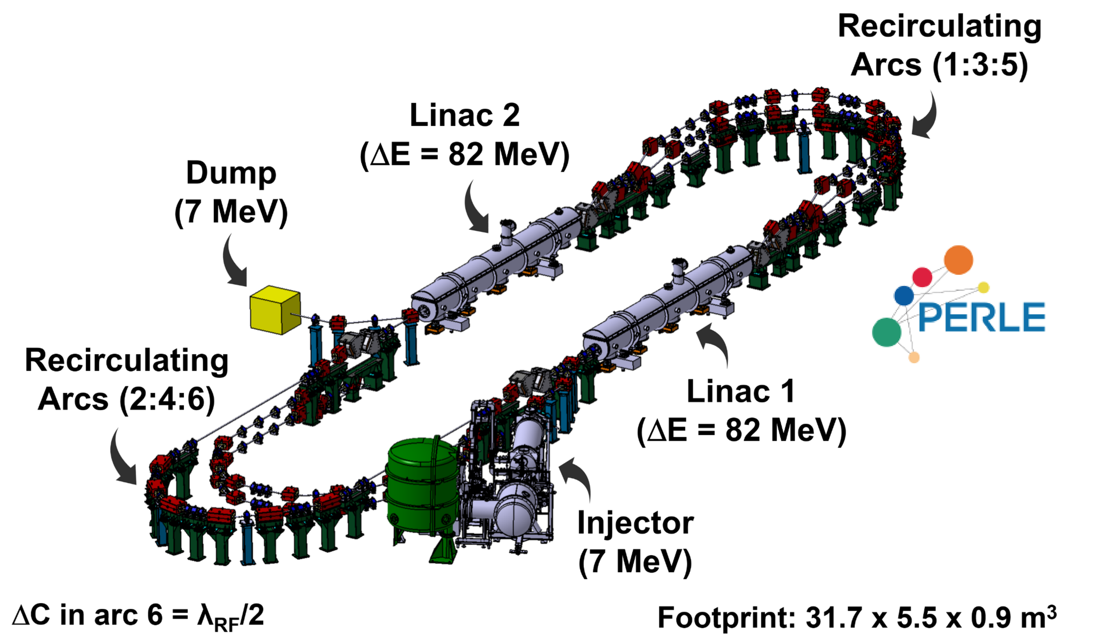
Introduction

PERLE (Powerful Energy Recovery Linac for Experiments) is a novel multi-turn* energy recovery linac (ERL) based on superconducting RF (SRF) technology currently under study and later to be hosted at Orsay in France.



Target Parameter	Unit	Value
Injection energy	MeV	7
Electron beam energy	MeV	500
Normalized Emittance $\gamma\varepsilon_{x,y}$	mm·mrad	6
Average beam current	mA	20
Bunch charge	pC	500
Bunch length	mm	3
Bunch spacing	ns	25
RF frequency	MHz	801.58
Duty factor	CW (Continuous Wave)	

*3 turns (164 MeV/turn): 3 passes "up" to reach the maximum energy, 3 passes "down" for energy recovery.

For high-current ERL, a relevant effect is multi-pass BBU which emerges when the electron beam interacts with the Higher Order Modes (HOMs) of the cavity, giving rise to beam instabilities and increasing the cryogenic load. Using HOM couplers with strong damping requirements becomes fundamental to limiting multi-pass BBU in the studied cavity.

SRF Cavity Design

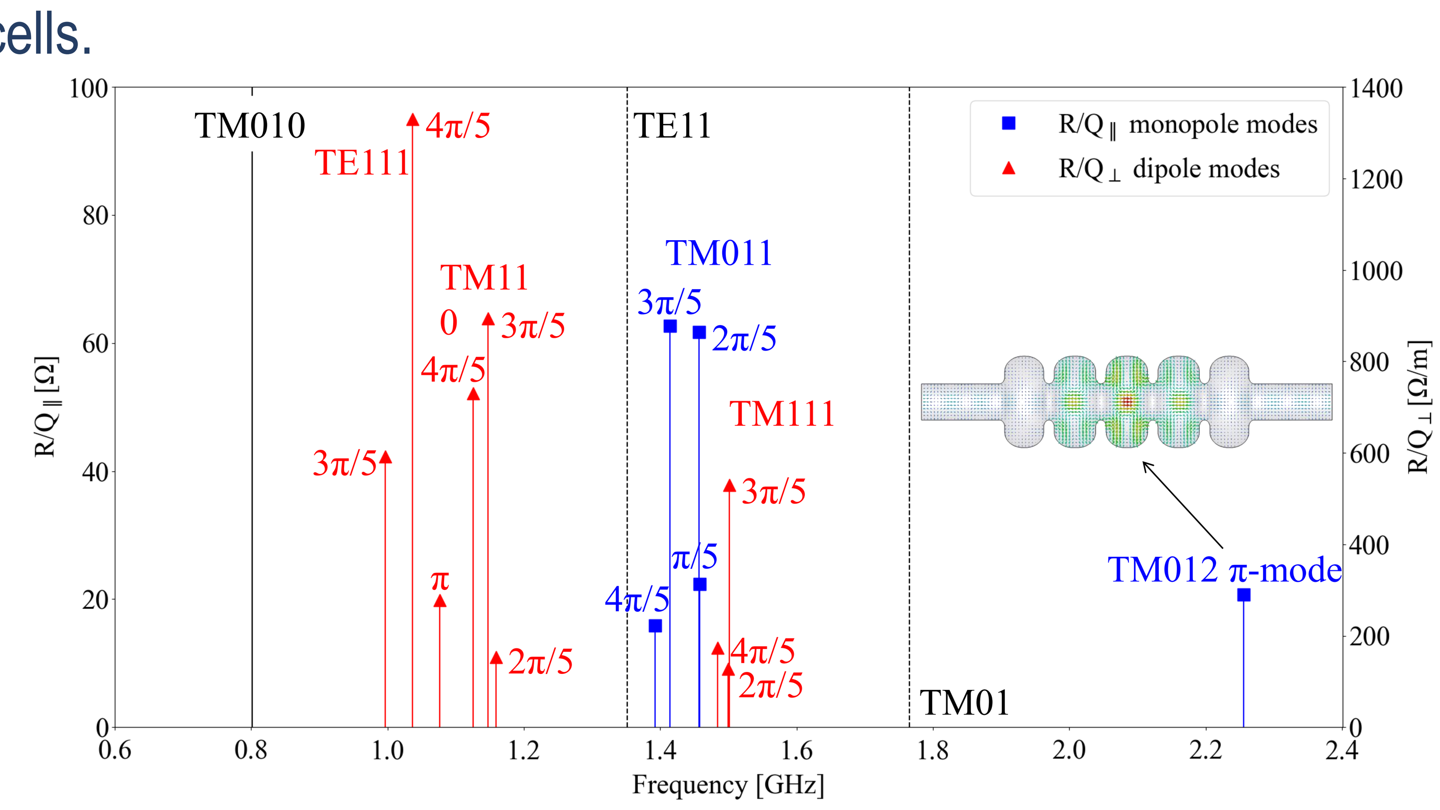
The first 5-cell 801.58 MHz Nb bare cavity suitable for PERLE was designed, fabricated, and successfully tested at JLab in 2018.

Parameters	JLab Cavity
Frequency [MHz]	801.58
Temperature [K]	2.0
Cavity active length [mm]	917.911
Mid-cell length [mm]	187.107
End-cell length [mm]	178.295
R/Q [Ω]	524.25
(R/Q)/(cell number) [Ω]	104.85
Geometry Factor (G) [Ω]	274.505
G*(R/Q) [Ω²]	143909.25
B_{pk}/E_{acc} (mid-cell) [mT/(MV/m)]	4.62
E_{pk}/E_{acc} (mid-cell) [-]	2.38
Iris radius [mm]	65
Beam Pipe radius [mm]	65
Mid-cell equator diameter [mm]	328
End-cell equator diameter [mm]	328
Wall angle [degree]	0

The cavity design 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 ($E_{pk}/E_{acc} = 2.38$, $B_{pk}/E_{acc} = 4.62\ \mathrm{mT/MV/m}$).

Higher Order Modes

HOMs are parasitic excited eigenmodes in an accelerating RF cavity, other than and with a frequency greater than the fundamental mode. Typically, the most problematic parasite modes are the first two dipole modes (TE111 and TM110) and the first monopole mode (TM011), which usually reside below the corresponding beam tube cutoff and possess high R/Q values. The TM012 π-mode appears at around 2.25 GHz and remains confined within the cavity mid-cells.



Numerical Methods

Time-domain wakefield and frequency-domain eigenmode simulations were carried out in CST Studio Suite® to calculate the cavity broadband HOM impedance spectra and identify the dangerous BBU HOMs.

Eigenmode simulations

Longitudinal impedance [Ω]

$$R_{||} = \left(\frac{R}{Q}\right)_{||} \cdot Q_l = \frac{V^2_{||(r=0)}}{\omega U} \cdot Q_l$$

Transverse impedance [Ω/m]

$$R_{\perp} = \left(\frac{R}{Q}\right)_{\perp} \cdot Q_l = \frac{\left(V_{||(r=r_0)} - V_{||(r=0)}\right)^2}{k r_0^2 \omega U} \cdot Q_l$$

Wakefield simulations

Longitudinal impedance [Ω]

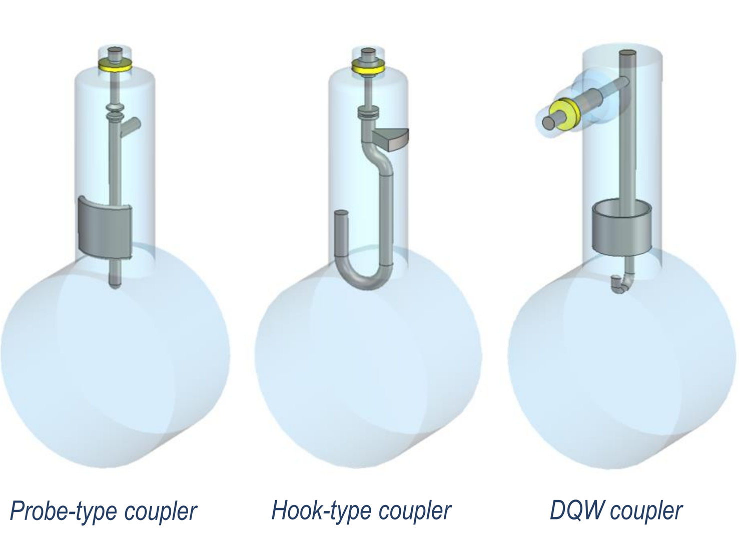
$$Z_{||}(\mathbf{r}, \omega) = \frac{1}{c}\int_{-\infty}^{\infty} w_{||}(\mathbf{r}, s)\, e^{-\frac{j\omega s}{c}} ds$$

Transverse impedance [Ω/m]

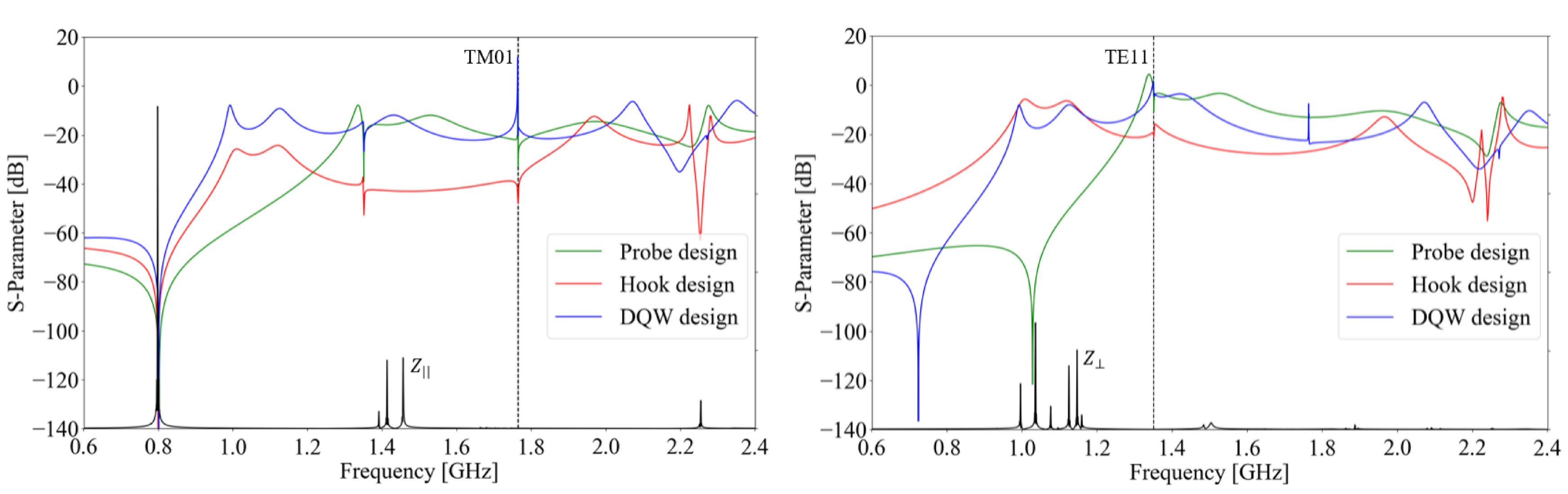
$$\mathbf{Z}_{\perp}(\mathbf{r}, \omega) = \frac{c}{\omega r_0} \nabla_{\perp} Z_{||}(\mathbf{r}, \omega)$$

To provide beam stability, the impedance of the most dangerous mode has to be reduced below the impedance instability thresholds ($Z_{||}^{\mathrm{th}}$ for monopole modes and $Z_{\perp}^{\mathrm{th}}$ for dipole modes), which can be computed via BBU analyses for an ERL.

HOM Couplers

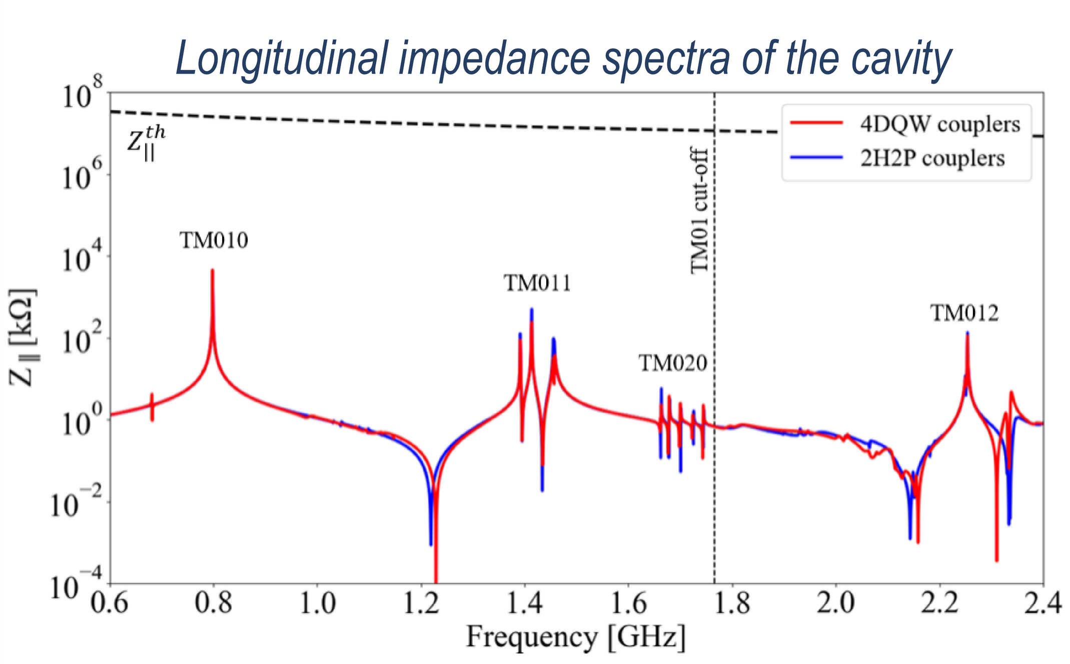


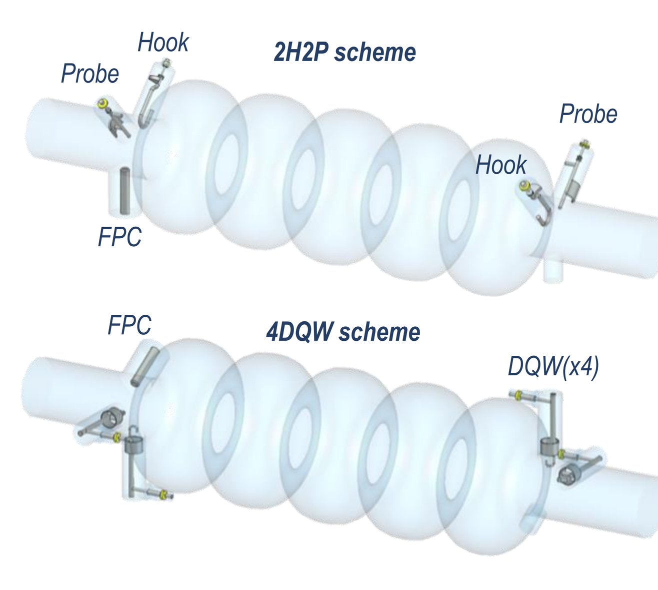
HOM couplers were optimized according to the HOM spectrum of the cavity using the 3D frequency domain solver of CST. The S-parameters between each excitation mode at the beam pipe port, simulating the field pattern inside the cavity, and the port at the coaxial output of the coupler are studied.

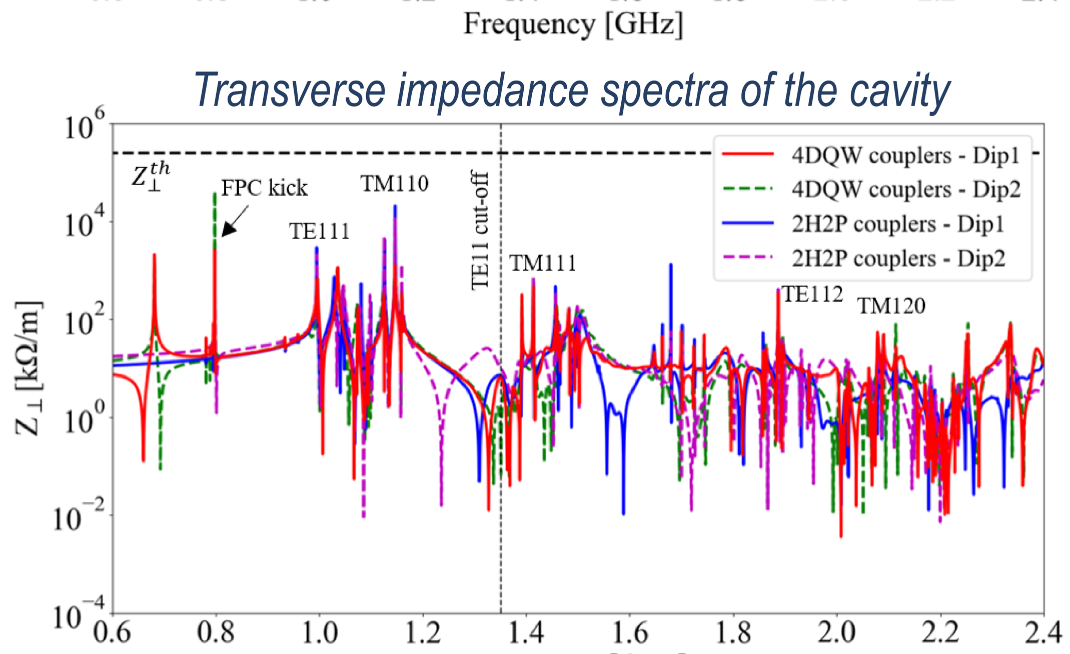


The hook coupler provides higher damping of the first two dipole passbands, while the DQW coupler exhibits a better monopole coupling for modes around 1.43 GHz than the probe design.

Impedance spectrum







The damping scheme with four DQW couplers shows promising results in damping both monopole and dipole HOMs below the stability limit. HOM power needs to be studied to decide on a final end-group design for the PERLE cavity.