Study of a 5-Cell Elliptical Superconducting Cavity for a Multi-turn Energy Recovery Linac

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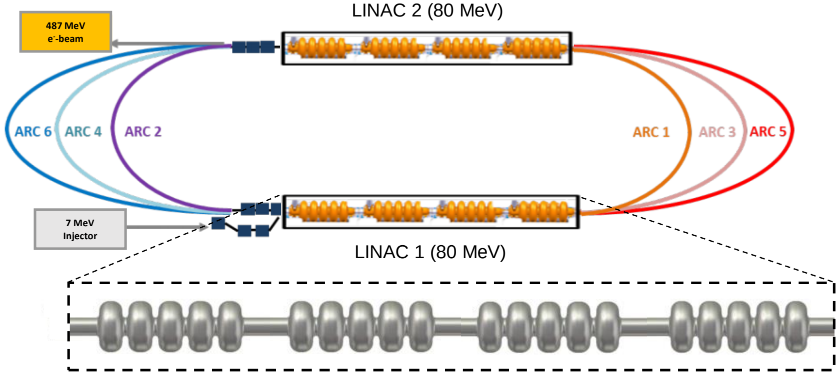
PERLE and 5-cell SRF cavity

- **PERLE** (**P**owerful **E**nergy **R**ecovery **L**inac for **E**xperiments): multi-turn ERL (Energy Recovery Linac) based on Superconducting RF (SRF) technology to be studied and later host at **Orsay** (France).



Four 5-cell 801.58 MHz elliptical Nb cavities

ARC 1 = 87 MeV
ARC 2 = 167 MeV
ARC 3 = 247 MeV
ARC 4 = 327 MeV
ARC 5 = 407 MeV
ARC 6 = 487 MeV

PERLE CDR, 2018 [1]

Target Parameter [2]	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)	

- The first 801.58 MHz 5-cell elliptical Nb cavity has already been fabricated at JLab on October 2017 [2]
- **HOM-damping for ERLs** is a challenge due to the presence of many turns (multi-bunch beam instabilities)
- Aim of the numerical study (CST Studio Suite®): 1) **Identification of HOMs**, 2) **Analysis of the transmission curves of HOM couplers**, 3) **HOM-damping schemes**

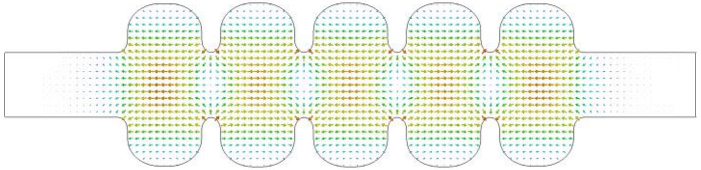
The first Nb 801.58 MHz 5-cell elliptical cavity fabricated at JLab [3].

Cavity Parameters	JLab Cavity
Frequency [MHz]	801.58
Temperature [K]	2.0
Cavity active length [mm]	917.911
R/Q [Ω]	524.25
Geometry Factor (G) [Ω]	274.505
B_{pk}/E_{acc} (mid-cell) $[\mathrm{mT/(MV/m)}]$	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
Cutoff TE_{11} [GHz]	1.35
Cutoff TM_{01} [GHz]	1.77

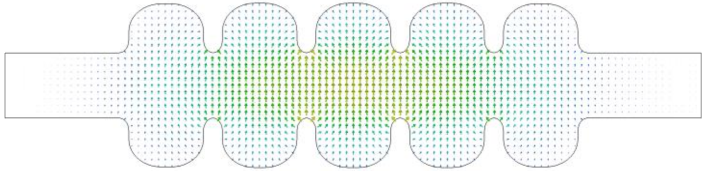
HOMs: consequences and damping mechanisms

- **HOMs** (**H**igher **O**rder **M**odes) are parasitic excited eigenmodes in a resonant accelerating RF cavity, other than and with frequency greater than the operational mode (**FM** = Fundamental Mode) [4].

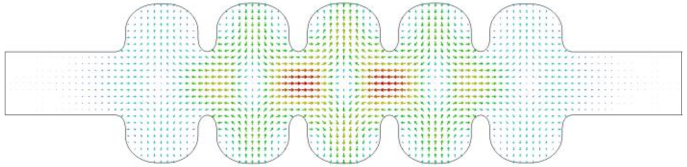
TM01-π mode (FM) – f =801.58 MHz



TE111 mode (Dipole HOM) – f =933.53 MHz



TM011 mode (Monopole HOM) – f =1374.73 MHz

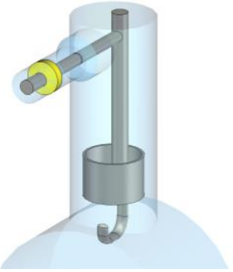


Why are HOMs dangerous for beam dynamics?

- **Monopole HOMs:**
  - can lead to **timing/phase errors** and **energy spread**
  - contribute to extra **dynamic heat losses** in cavity walls
- **Dipole HOMs:**
  - can **deflect the beam** from its reference orbit: instable beam motion, transverse emittance growth, beam loss

How can we damp HOMs in SRF cavities?

- **Coaxial HOM coupler on beam tubes**
  - Hook-type LHC coupler
  - Probe-type LHC coupler
  - DQW HOM coupler
- Waveguide dampers on beam tubes
- Absorbers in cavity-interconnecting beam tubes
- Coupling through Fundamental Power Coupler



DQW HOM Coupler

HOM numerical simulations: 3D-Eigenmode and Wakefield

- The **eigenmodes** of a resonator in a non-excited source-free and lossless medium are computed by solving the Helmholtz equations:

Helmholtz equations

$$\nabla^2 \underline{\mathbf{E}} + \omega^2 \mu\varepsilon \underline{\mathbf{E}} = 0$$

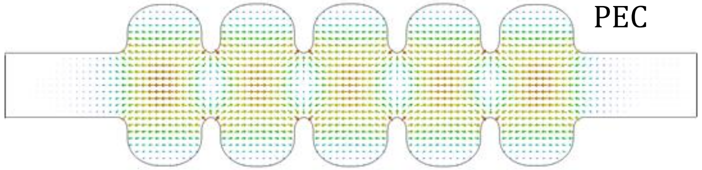
$$\nabla^2 \underline{\mathbf{H}} + \omega^2 \mu\varepsilon \underline{\mathbf{H}} = 0$$

Boundary conditions

$\mathbf{n} \times \underline{\mathbf{E}} = 0$ and $\mathbf{n} \cdot \underline{\mathbf{H}} = 0$ on $\partial\boldsymbol{\Omega}_{\mathrm{PEC}}$

$\mathbf{n} \cdot \underline{\mathbf{E}} = 0$ and $\mathbf{n} \times \underline{\mathbf{H}} = 0$ on $\partial\boldsymbol{\Omega}_{\mathrm{PMC}}$

TM01-π mode (FM) – f =801.58 MHz



Assumption: PEC (Perfect Electric Conductor) on conducting walls (Nb) and interior domain of vacuum

- Cavity-beam interaction: **wakefields** in time domain or **impedances** in frequency domain. The long-range wakefield commonly corresponds to the **high impedance peaks** and can lead to coupled-bunch instability issues [4].

Eigenmode simulations

Longitudinal shunt impedance [Ω]

$$\frac{R}{Q_{||,n}} = \frac{V^2_{||,n}(0,0)}{\omega_n U_n}$$

Transverse shunt impedance [Ω/m]

$$\frac{R}{Q_{t,n}} = \frac{V^2_{||,n}(r)}{\omega_n U_n} \cdot \frac{c}{\omega_n} \frac{1}{r^2}$$

Wakefield simulations

Longitudinal impedance [Ω]

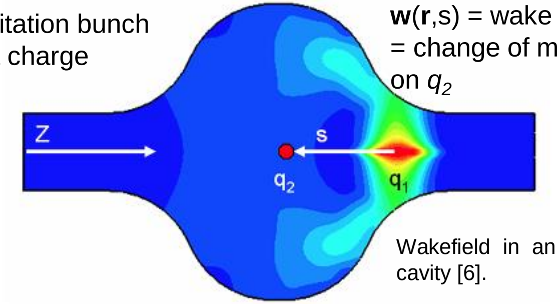
$$Z_{\mathrm{L}}(\mathbf{r},\omega) = \frac{1}{c}\int_{-\infty}^{\infty} w_{\mathrm{L}}(\mathbf{r},s)\, e^{-\frac{j\omega s}{c}} ds$$

Transverse impedance [Ω/m]

$$\boldsymbol{Z}_{\mathbf{T}}(\mathbf{r},\omega) = \frac{-j}{c}\int_{-\infty}^{\infty} \boldsymbol{w}_{\mathbf{T}}(\mathbf{r},s)\, e^{-\frac{j\omega s}{c}} ds$$

q_1 = excitation bunch
q_2 = test charge

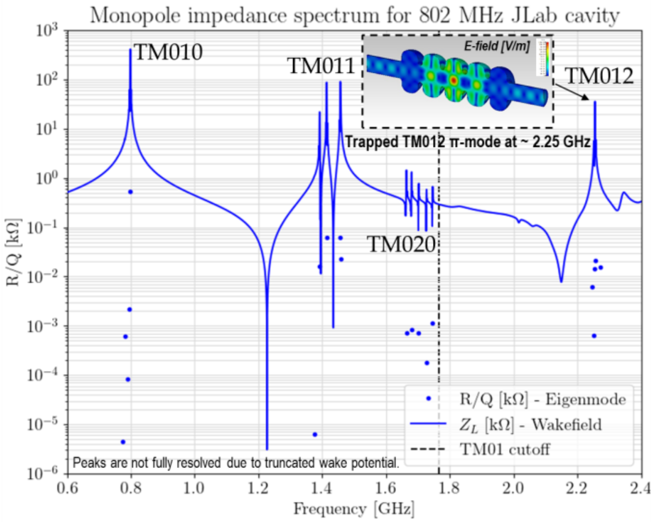
w(**r**,s) = wake potential = change of momentum on q_2

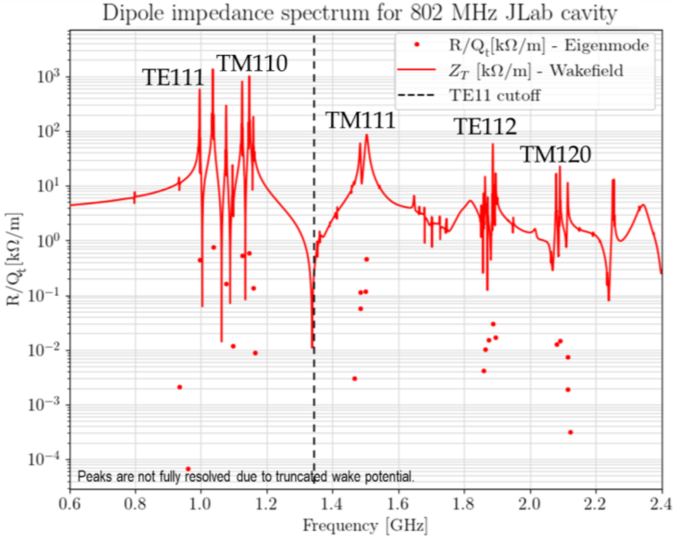


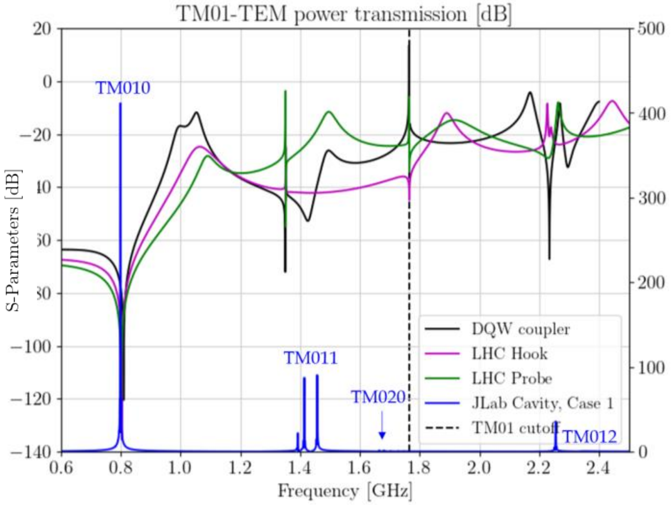
Wakefield in an elliptical cavity [6].

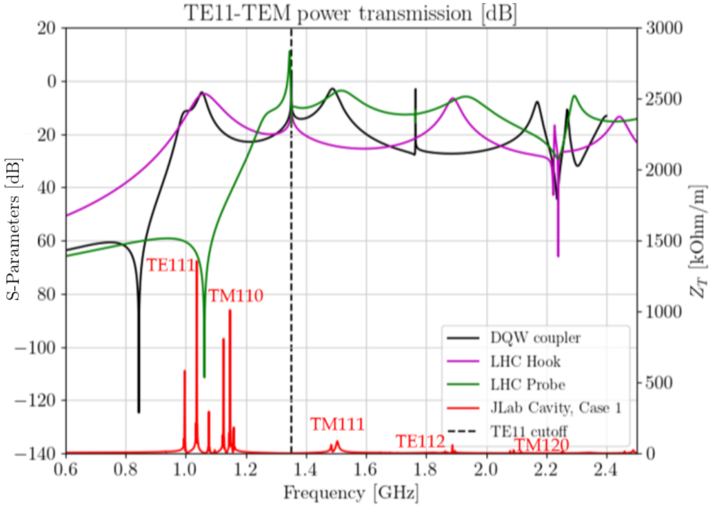
The energy left behind q_1 is called **wakefield**.

Identification of dangerous HOMs – HOM coupler transmission









TM monopole modes (like TM010, TM011, TM020, T012)

- E-field component along cavity axis
- Trapped mode can interact with the subsequent bunch

TM dipole modes (like TM110, TM111, TM120)

- Strong longitudinal E-field component off axis
- Possible deflection and subsequent beam resonant effect

TE dipole modes (like TE111, TE112)

- Theoretically no longitudinal E-field component on and off axis (possible deflection)

TM01-TEM transmission

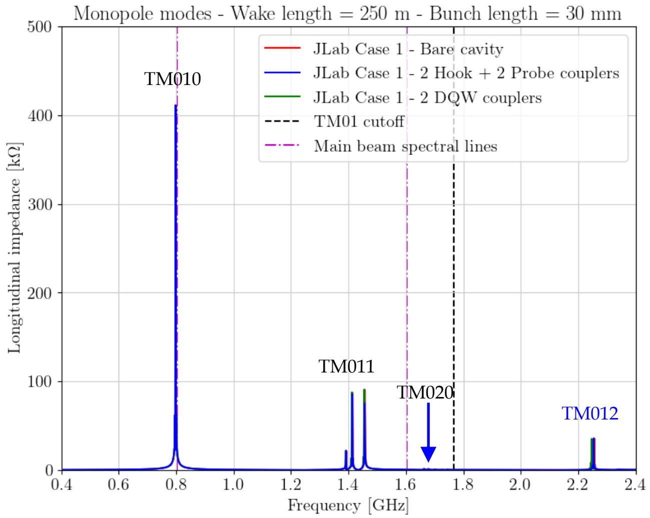
- The notch effect is tuned to 801.58 MHz for monopole coupling.
- Couplers optimization needed to deliver a higher value of transmission.

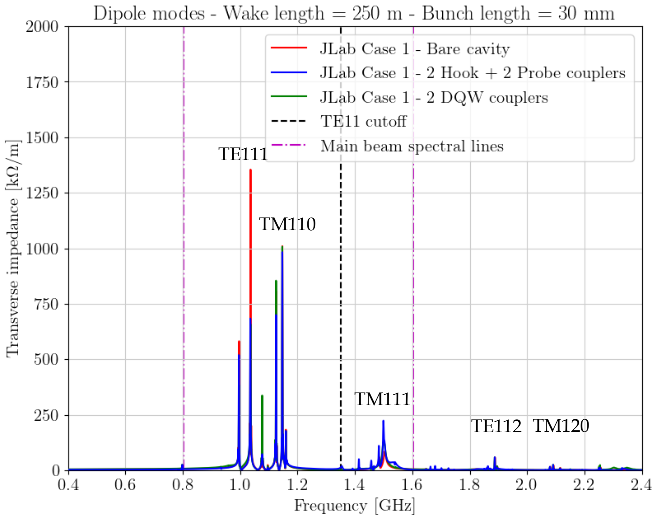
TE11-TEM transmission

- Hook coupler: higher transmission than DQW coupler for the TE111-type and TM110-type passband.

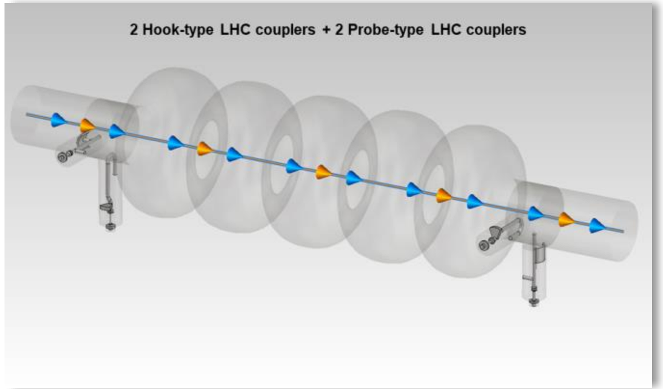
HOM-damping studies

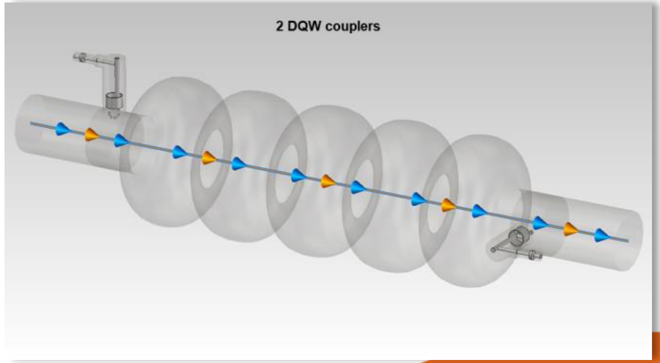
- **Objective**: extract the energy of the HOMs from the cavity.





HOM-damping schemes





Preliminary results for the two investigated configurations:

- 2 Hook + 2 Probe couplers configuration provides a better damping of both monopole and dipole HOMs than the 2DQW couplers

- However, the trapped TM012 mode was not damped in the two configurations (modification of the end-cells is needed to enhance the coupling to the beam tube)

Conclusions

- Eigenmode and wakefield analyses were carried-out in CST Studio Suite® to investigate on the HOM behavior of PERLE Cavity

- Potentially dangerous monopole and dipole HOMs were identified and classified until 2.4 GHz. A trapped monopole HOM was found at ~2.25 GHz

- HOM-damping scheme studies: 2 Hook + 2 Probe couplers configuration gives a better damping of both monopole and dipole HOMs than the 2DQW couplers

Future perspectives:

- Optimization of the cavity end-cells to improve the coupling of the TM012 π-mode to the beam tubes

- Optimization of HOM couplers, and study of other HOM couplers (JLAB, TESLA)

- Thermal studies for HOM couplers (HOM power and dissipation)

Bibliography

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Thank you for your attention!

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