Séminaires doctorants 2ème année, June 8th 2022

Preliminary results on High-Order-Mode damping studies for the PERLE cavity

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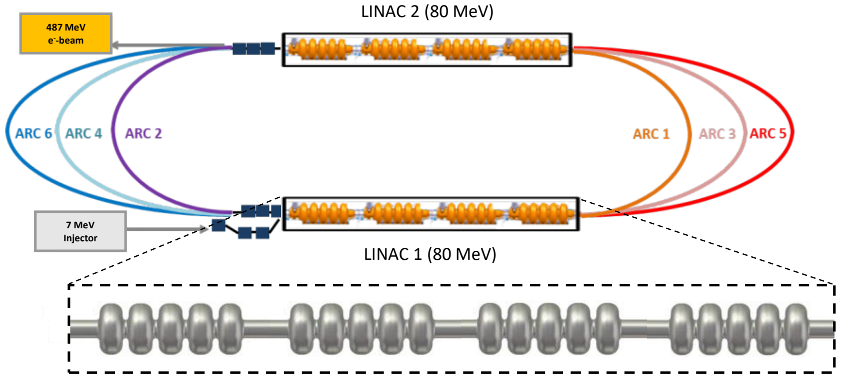
PERLE and the 5-cell SRF cavity

- **PERLE** (**P**owerful **E**nergy **R**ecovery **L**inac for **E**xperiments): multi-turn ERL (Energy Recovery Linac) based on Superconducting RF (SRF) technology currently under study and later to be hosted 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

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)	

- Testbed for studying a wide range of accelerator phenomena
- 2 Linacs (four 5-cell 801.58 MHz SC cavities)
- 3 turns (160 MeV/turn): 3 passes “up” to reach the maximum electron beam energy (500 MeV), 3 passes down for the energy recovery phase
- The first 801.58 MHz 5-cell elliptical Nb cavity has already been fabricated at JLab in October 2017
- **HOM-damping for ERLs** is a challenge due to the presence of many turns (losses and multi-bunch beam instabilities)

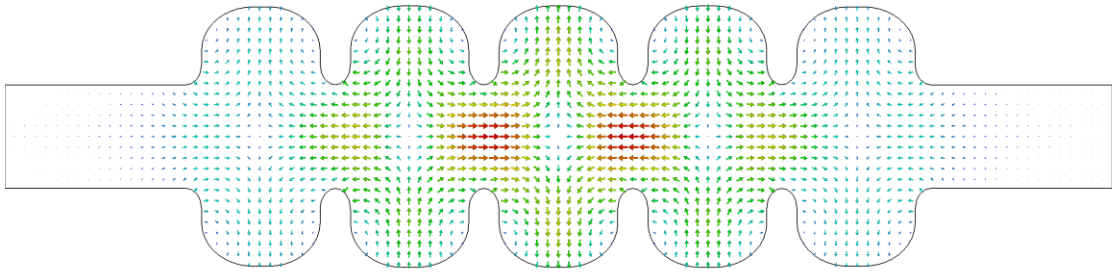
The first fabricated Nb 801.58 MHz 5-cell elliptical cavity at JLab.

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) [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

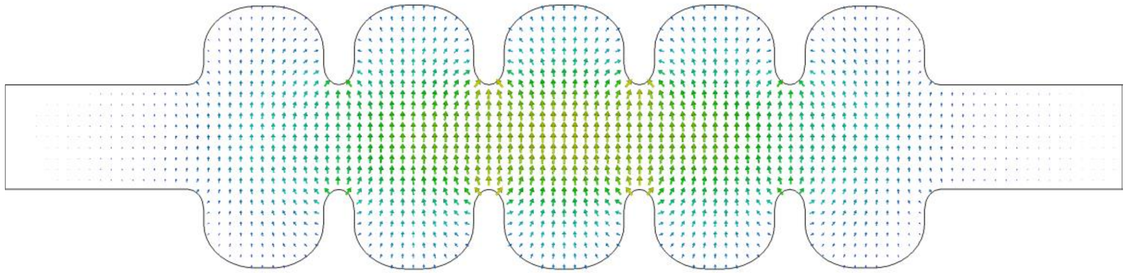
HOMs: consequences and damping mechanisms

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

E-field - TM011 mode (Monopole HOM) – f =1374.73 MHz

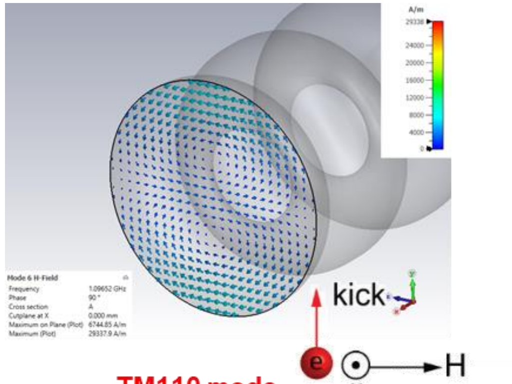


E-field - TE111 mode (Dipole HOM) – f =933.53 MHz



Why are HOMs dangerous for beam dynamics?

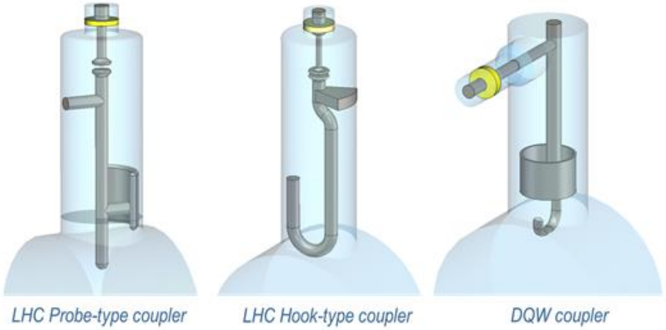
- Monopole HOMs:
  - can lead to **timing/phase errors** and **energy spread**
  - contribute to extra **dynamic heat losses** in cavity walls
- Dipole HOMs:
  - can **deflect the beam** from its reference orbit: unstable beam motion, transverse emittance growth, beam loss



TM110 mode

How can we damp HOMs in SRF cavities?

- **Coaxial HOM coupler on beam tubes**



HOM numerical simulations (CST Studio Suite®)

- **3D-Eigenmode simulations (cavity) – Frequency domain**

Helmholtz equations

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

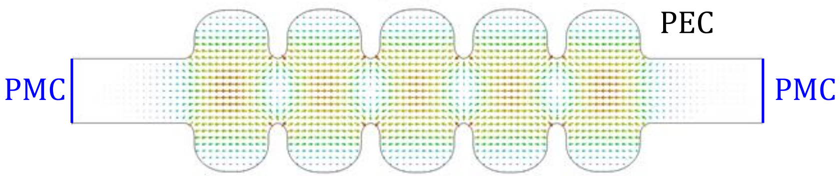
$$\nabla^2 \underline{\mathbf{H}} + \omega^2 \mu\varepsilon \underline{\mathbf{H}} = 0$$

Boundary conditions

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

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

TM01-π mode (FM) – f =801.58 MHz



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

- **3D-Wakefield simulations (cavity-beam interaction) – Time domain**

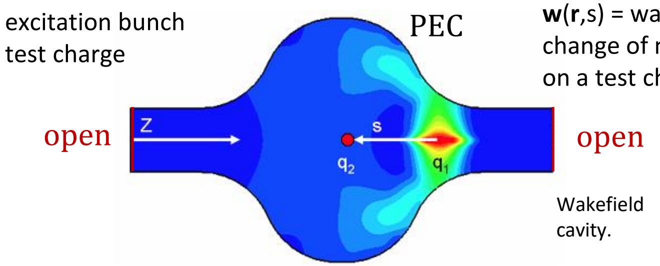
Wake function

$$\boldsymbol{w}(\mathbf{r}, s) = \frac{1}{q_1 q_2} \int_{-\infty}^{+\infty} dz q_2 [\mathbf{E}(\mathbf{r}, z, t) + c\hat{\mathbf{z}} \times \mathbf{B}(\mathbf{r}, z, t)]_{t=(s+z)/c}$$

Impedance in frequency domain (FFT of the wake function)

$$\boldsymbol{Z}(\omega) = \int_{-\infty}^{+\infty} dt\, \boldsymbol{w}(t) e^{-j\omega t}$$

q_1 = excitation bunch
q_2 = test charge

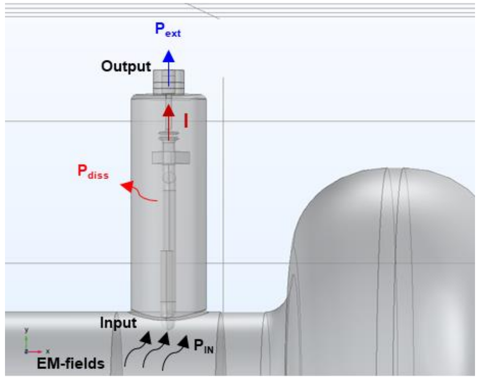


w(**r**,s) = wake function = change of momentum on a test charge q_2

Wakefield in an elliptical cavity.

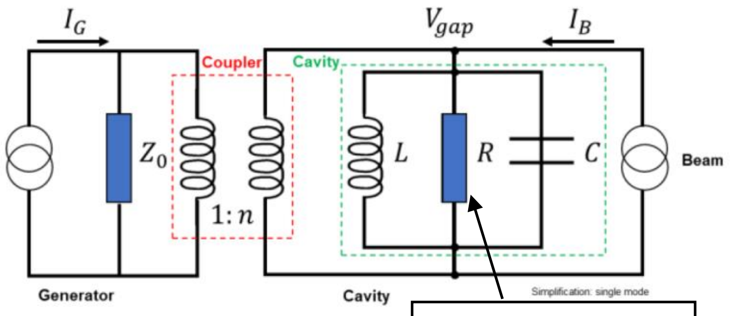
The energy left behind q_1 is called **wakefield**.

- **HOM-coupler power transmission – Frequency domain**
  - S-parameter [dB] calculation
  - Coupler optimization
  - Thermal studies



3D-Eigenmode simulation: HOM identification

- In a cavity the beam excites a voltage along the so-called **shunt impedance R_s**



$$P_{diss} = \frac{R_s}{2}\int_{S_{cav}} |\boldsymbol{H}|^2\, dS$$

- **R/Q** represents the interaction between the beam and the RF field inside the cavity. It depends on the cavity geometry only.
- **Dangerous HOMs** have high R/Q values (TM011 monopole and TE111, TM110 dipole with R/Q>10 Ohm)

Longitudinal R/Q [Ω]

$$\frac{R}{Q}_{l,n} = \frac{\left|V_{l,n}(0,0)\right|^2}{\omega_n U_n}$$

Transverse R/Q [Ω]*

$$\frac{R}{Q}_{tr,n} = \frac{\left|V_{x,n}(0,0)\right|^2}{\omega_n U_n} + \frac{\left|V_{y,n}(0,0)\right|^2}{\omega_n U_n}$$

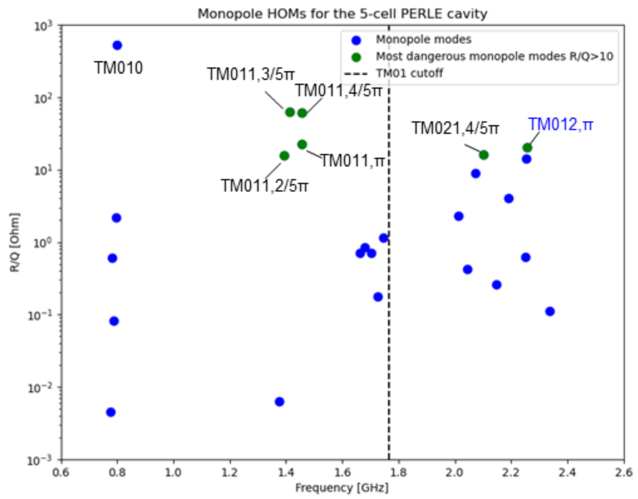
*also in [Ω/m] in the literature

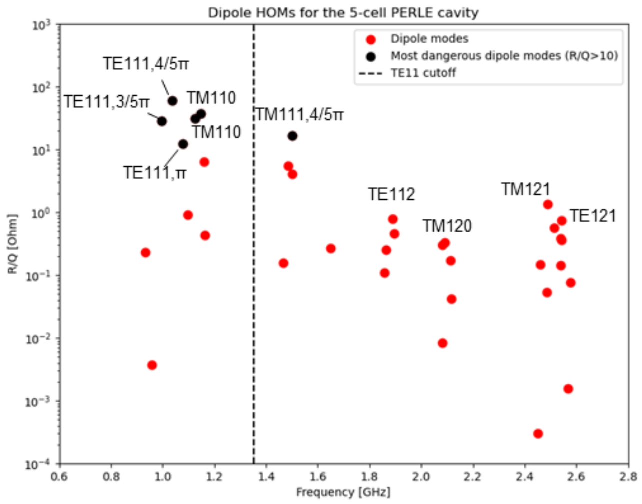
Shunt Longitudinal impedance [Ω]

$$R_l = \frac{R(r=0)}{Q}\cdot Q_L$$

Shunt Transverse impedance [Ω/m]

$$R_{tr} = \frac{R(r)}{Q}\cdot Q_L \cdot \frac{1}{kr^2}$$





R/Q and TM01-TEM for monopole HOMs (bare cavity)

Mode	f [GHz]	R/Q [Ω]
TM011,2/5π	1.392	15.829
TM011,3/5π	1.414	62.516
TM011,4/5π	1.457	61.524
TM011,π	1.458	22.355
TM021,4/5π	2.103	16.110
TM012,π	2.256	20.573

R/Q and TE11-TEM Polar 1 for dipole HOMs (bare cavity)

Mode	f [GHz]	R/Q [Ω]
TE111,3/5π	0.996	28.356
TE111,4/5π	1.036	61.016
TE111,π	1.077	12.302
TM110	1.125	30.936
TM110	1.147	37.187
TM111,4/5π	1.501	16.840

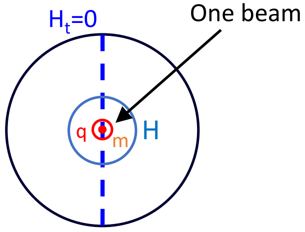
- Damping HOMs means reducing the **shunt impedance**, having a lower loaded quality factor Q_L

$$\frac{1}{Q_L} = \frac{P_{loss}}{\omega_n U_n} = \frac{P_{cav} + P_{ext,1} + P_{ext,2} + \cdots}{\omega_n U_n}$$

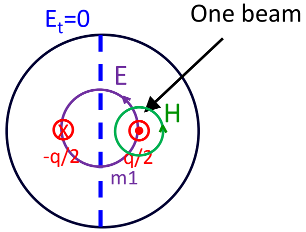
- **Higher the power extracted P_{ext}** from the HOM-couplers, lower Q_L, and lower the shunt impedance for the HOMs

Wakefield simulation: Multi-beam Excitation Scheme and Customized FFT script

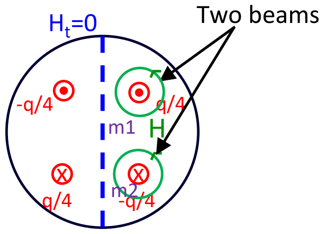
- The implemented method allows to separately excites monopole, and dipole modes, suppressing unwanted modes.



Monopole modes



Dipole modes – polar 1



Dipole modes – polar 2

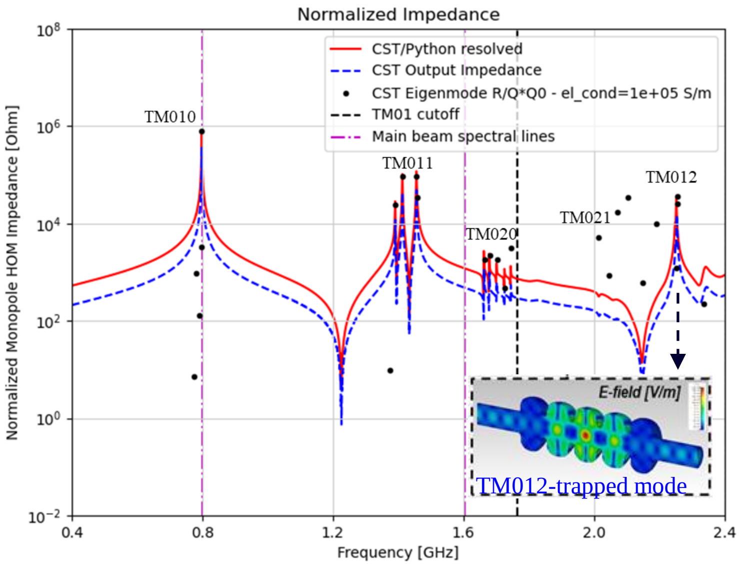
- We built with JLab a customized FFT script in Python which allows solving impedance peaks more accurately than in CST (a factor 3 compared with the eigenmode solution)

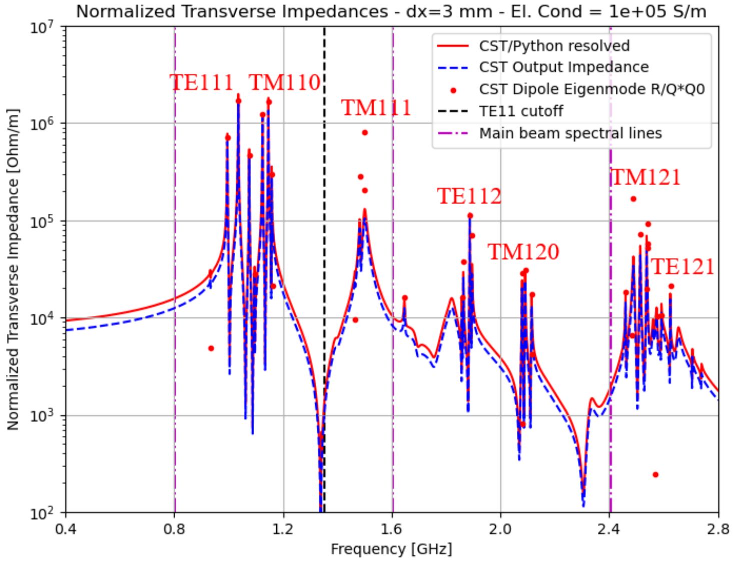
Longitudinal wake impedance [Ω]

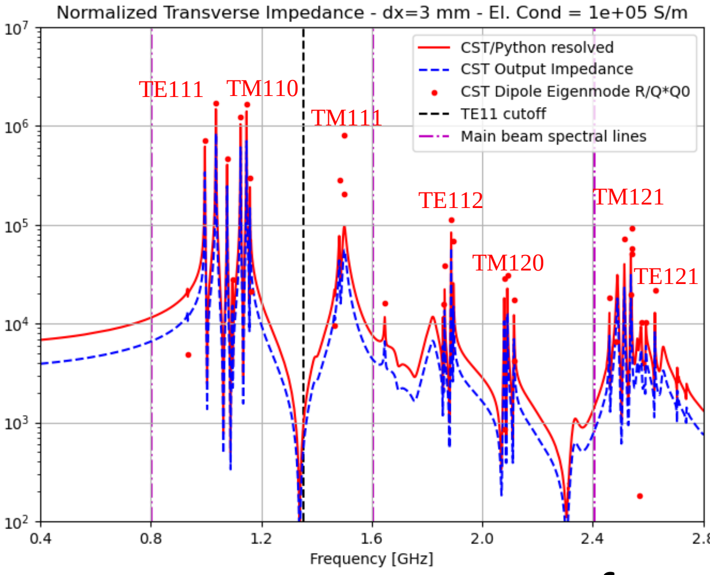
$$Z_{||}(\mathbf{r},\omega) = \frac{1}{c}\int_{-\infty}^{\infty} w_{||}(\mathbf{r},s)\, e^{-\frac{j\omega s}{c}} ds$$

Transverse wake impedance [Ω/m] – Panofsky-Wenzel Theorem

$$\mathbf{Z}_{\perp}(\mathbf{r},\omega) = -\frac{j\beta c}{\omega_n r^2}\nabla_{\perp} Z_{||}(\mathbf{r},\omega)$$







HOM coupler power transmission studies and coupler optimization

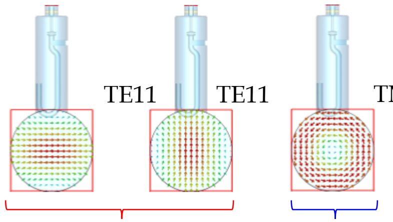
S-parameters [dB] simulation (frequency domain solver)

For a device with n ports

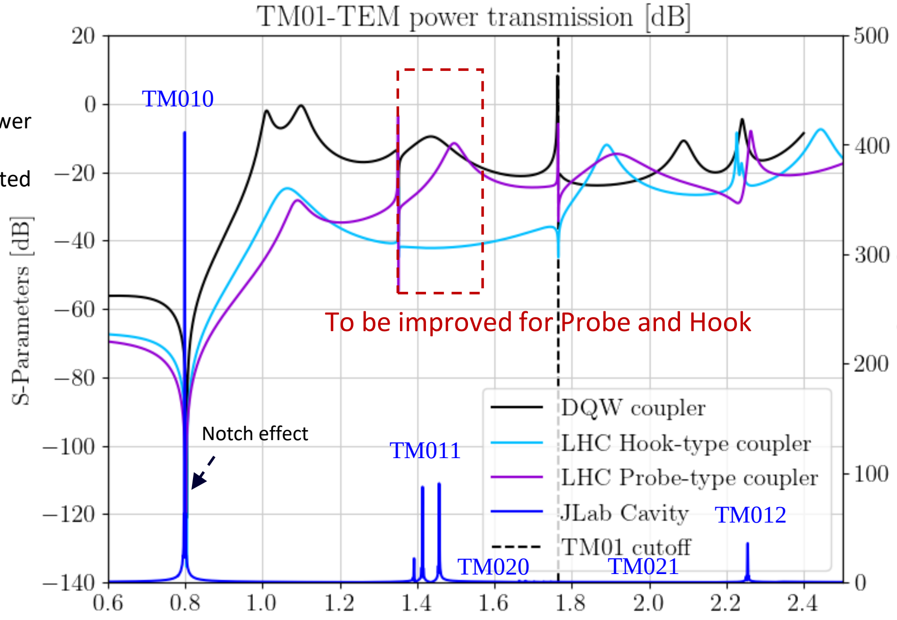
$$S = \begin{bmatrix} S_{11} & S_{12} & \cdot & \cdot & S_{1n} \\ S_{21} & S_{22} & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ S_{n1} & \cdot & \cdot & \cdot & S_{nn} \end{bmatrix}$$

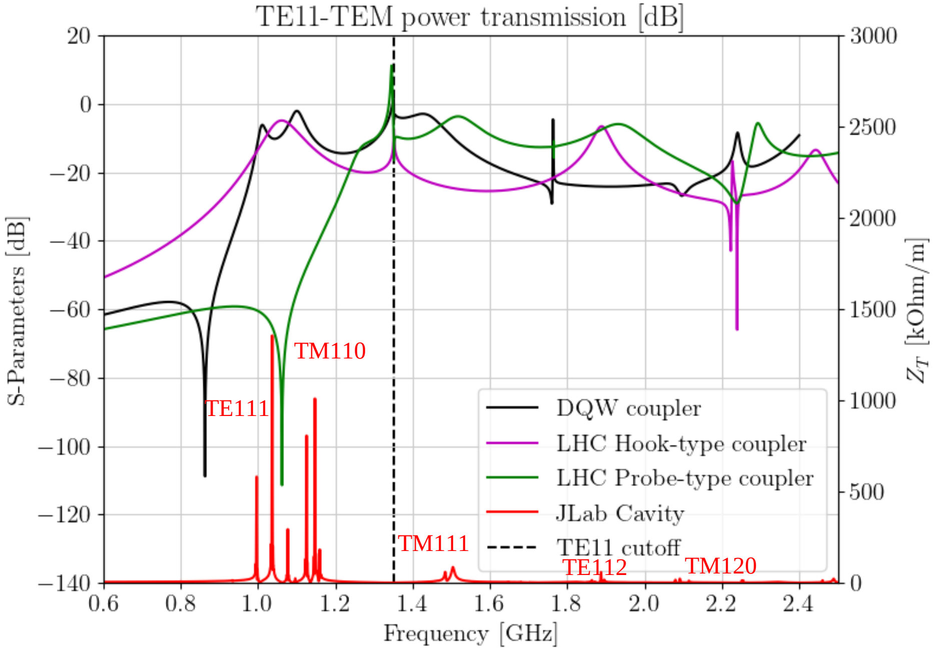
S_{ii} for reflected power

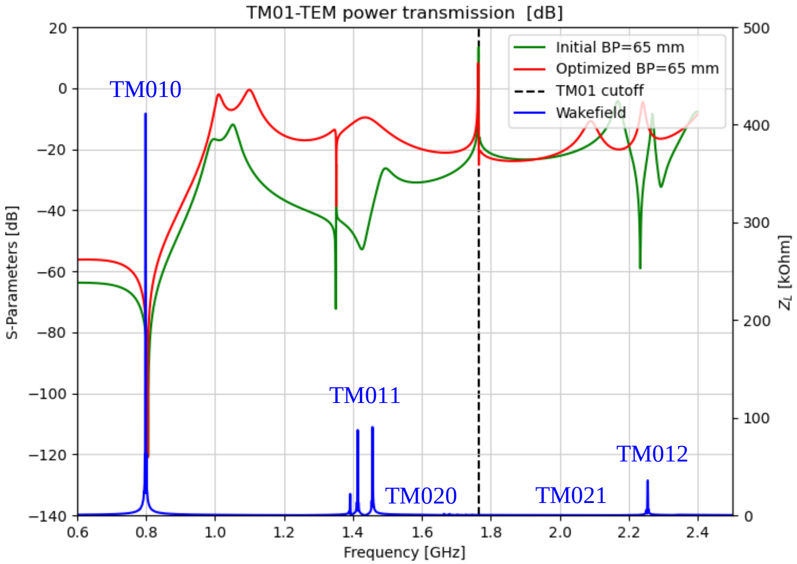
$\boldsymbol{S_{ij}}$ for the transmitted power

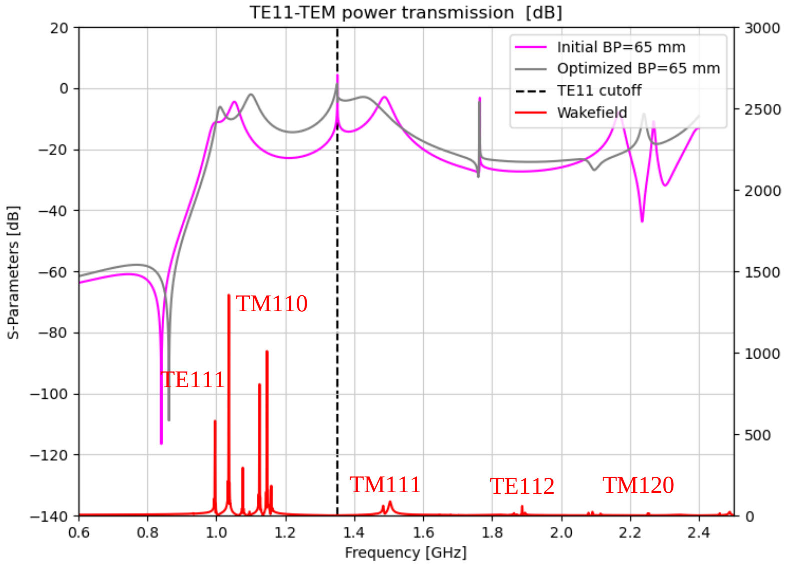


TE11-TEM coupling **TM01-TEM coupling**

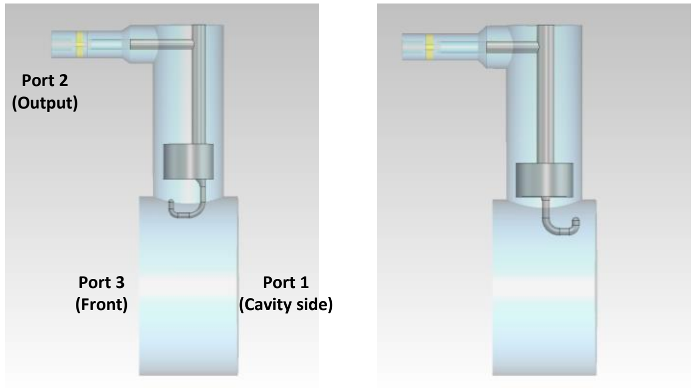








Original geometry **Optimized geometry**



DQW coupler optimization

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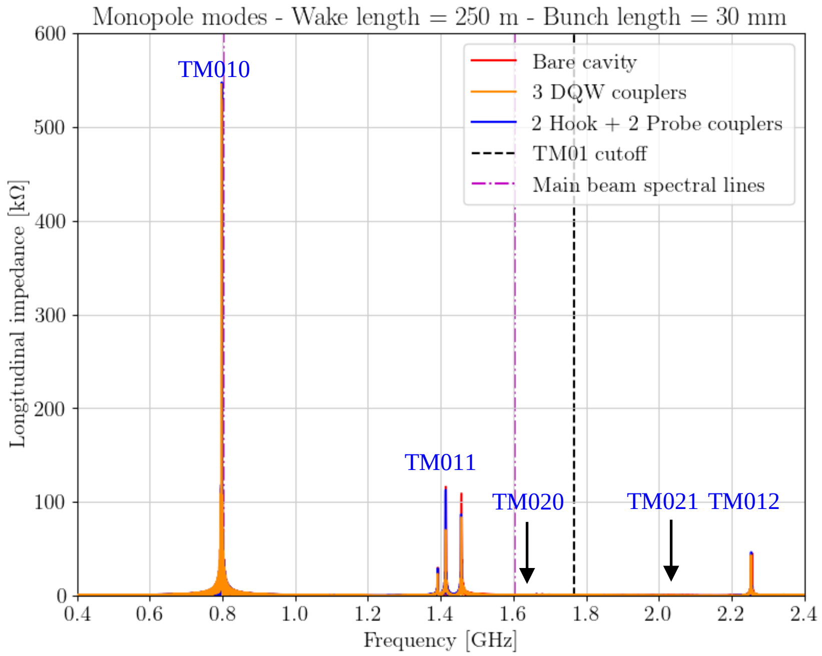
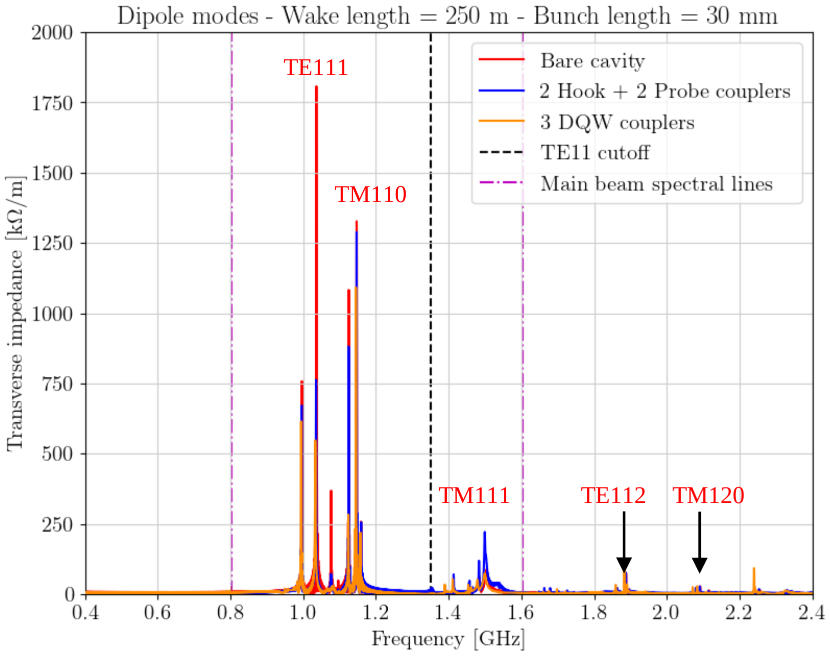
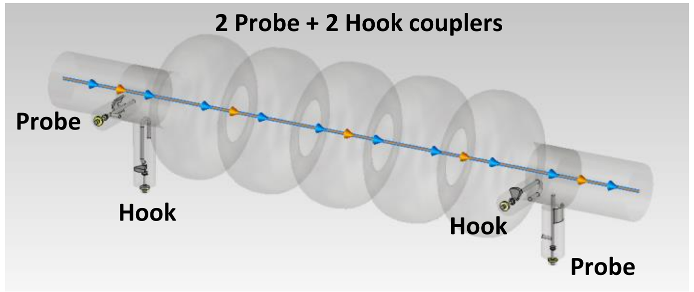
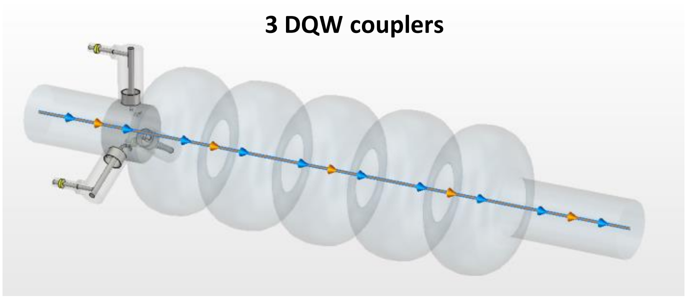
HOM-damping schemes (5-cell cavity + HOM couplers)

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





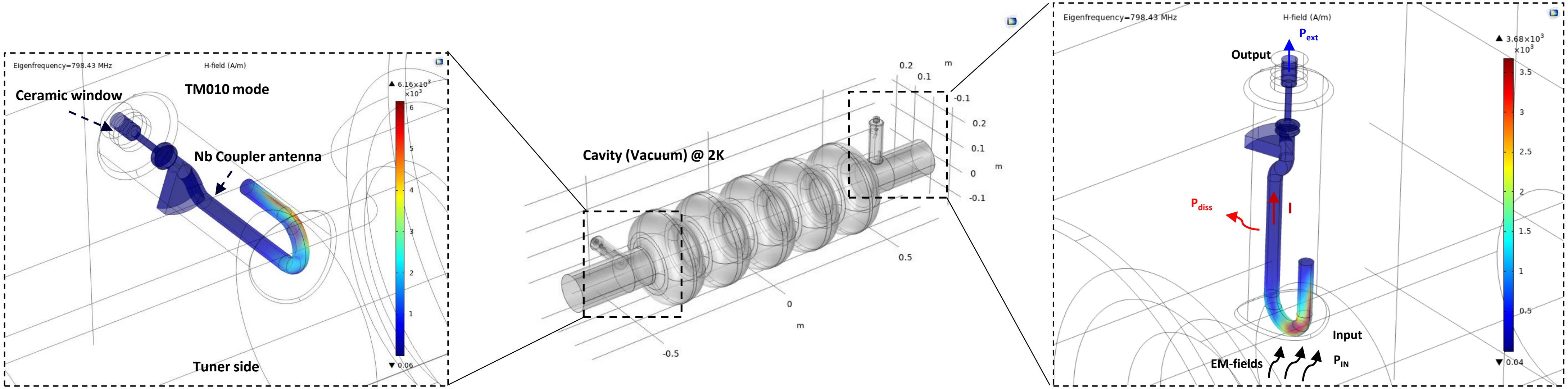




Preliminary results:

- 3 DQW couplers seem to provide better damping than 2 Hook + 2 Probe couplers configuration both for dipole and monopole HOMs. However, Hook and Probe couplers need further optimization.
- The transverse impedance of the TM111 mode strangely increases in the 2 Hook + 2 Probe configuration. This is maybe due to the asymmetrical structure of the end-groups in this particular case.
- Beam-stability impedance thresholds for an ERL are needed to determine the maximum allowed impedance.

RF-Heating Analysis (COMSOL Multiphysics®) – Ongoing studies



Power coupler side

$$B_{FM_{max}} = \mu_0 H_{FM} = 7.74\ mT$$

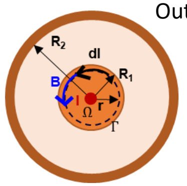
$$B_{FM_{max}} = \mu_0 H_{FM} = 4.62\ mT$$

- Electric surface current for the ith HOM

$$I_i^2 = \int_{S_{coupler}} \boldsymbol{H}_i \cdot \boldsymbol{H}_i^* dS = \int_{S_{coupler}} |\boldsymbol{H}_i|^2 dS\ [A^2]$$

- Extracted power from coupler port for the ith HOM

$$P_{ext,i} = \frac{1}{2} Re \int_{R_1}^{R_2} (\boldsymbol{E}_i \times \boldsymbol{H}_i^*) dS \quad [W]$$



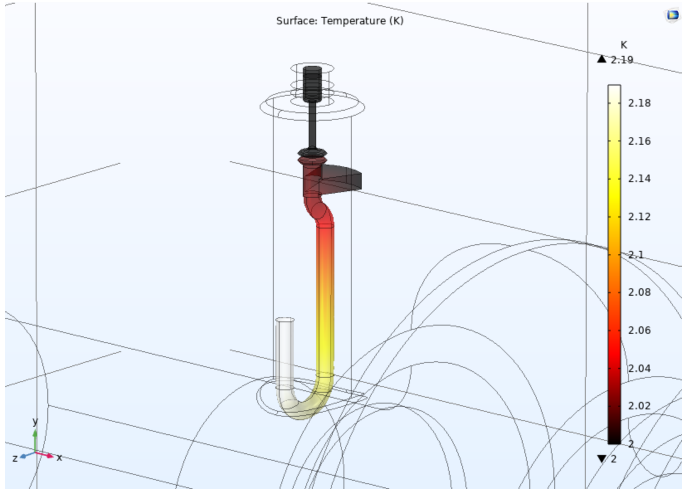
Output port of HOM coupler

- Power dissipation on the coupler antenna for the ith HOM

$$P_{diss,i} = \frac{1}{2} R_s(T) I_i^2 \quad [W]$$

Heat-flux source for the thermal analysis

Thermal map of the coupler antenna (feedthroughs are fixed at 2 K)



Conclusions and perspectives

Conclusions:

- Eigenmode and wakefield analyses were carried-out in CST Studio Suite® to investigate 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: 3 DQW couplers seem to provide better damping than 2 Hook + 2 Probe couplers configuration both for dipole and monopole HOMs. However, Hook and Probe couplers need further optimization.

Future studies:

- Study of new HOM-damping schemes and HOM couplers (Tesla coupler, Waveguide)
- Improve the TM01-TEM transmission of Hook and Probe couplers
- Determine beam stability thresholds for longitudinal and transverse impedance
- Compute the H-field and thermal maps of the coupler antenna for the HOMs of the cavity, and evaluate if an active cooling of the coupler antenna is required.

Thank you for your attention!

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