HOM-Damping Studies in a Multi-Cell Elliptical Superconducting RF Cavity for the Multi-Turn Energy Recovery Linac PERLE

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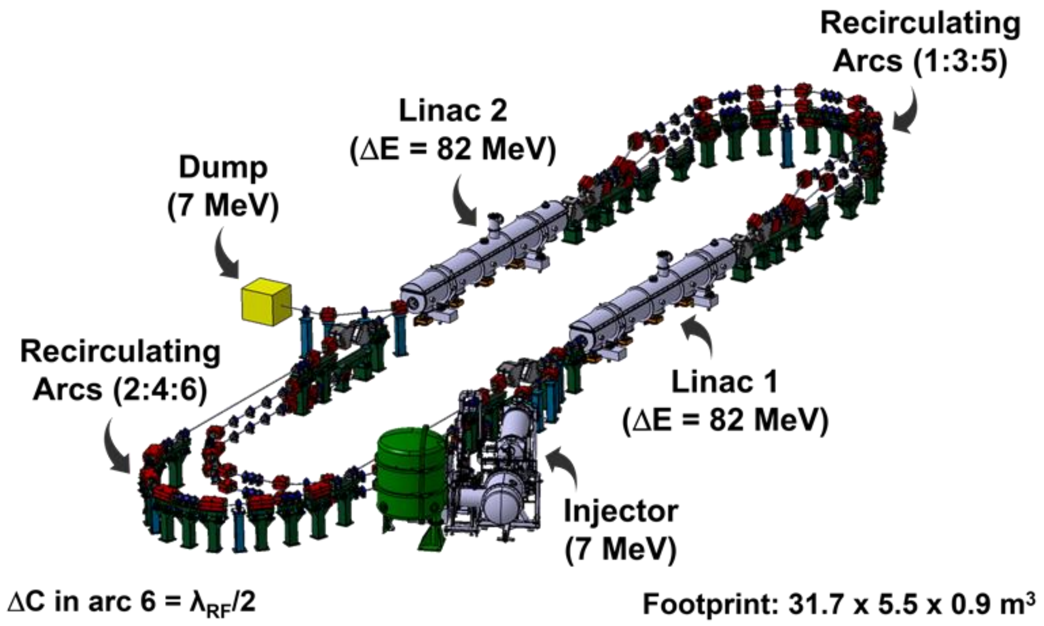
The PERLE accelerator complex

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



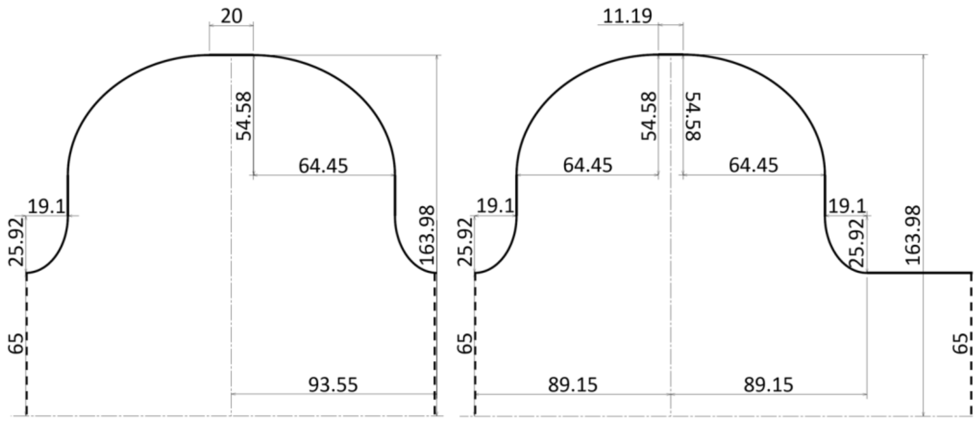
Target Parameter	Unit	Value
Injection energy	MeV	7
Electron beam energy	MeV	500
Normalized Emittance $\Upsilon\varepsilon_{x,y}$	mm·mrad	6
Average beam current	mA	20
Bunch charge	pC	500
Bunch length	mm	3
Bunch spacing	ns	25
RF frequency	MHz	801.58
Duty factor	CW (Continuous Wave)	

- Testbed for studying a wide range of accelerator phenomena
- 2 Linacs (four 5-cell 801.58 MHz SC cavities)
- 3 turns (164 MeV/turn): 3 passes “up” (E_{max}=500 MeV), 3 passes “down” (energy recovery phase)

The 5-cell SRF cavity for PERLE

The first 801.58 MHz 5-cell elliptical Nb cavity has already been fabricated and successfully tested at JLab in October 2017 [1].

Courtesy of F. Marhauser



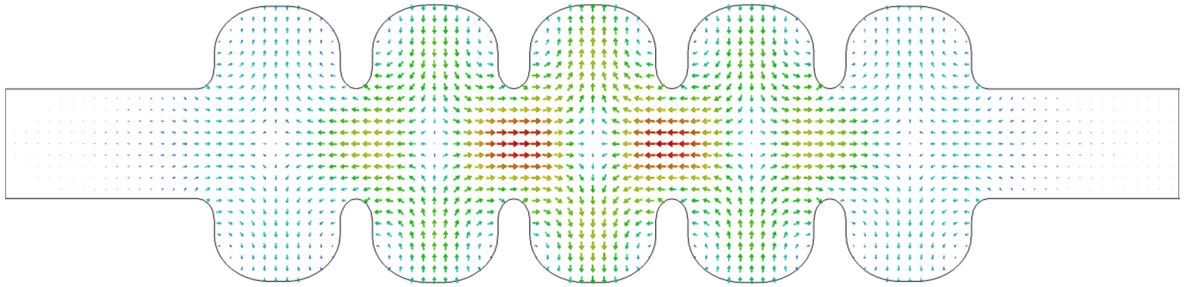
Mid-cell End-cell

Cavity Parameters	Unit	Value
Frequency	[MHz]	801.58
Temperature	[K]	2.0
Cavity active length	[mm]	917.9
R/Q	[Ω]	523.9
Geometry Factor (G)	[Ω]	274.6
B_{pk}/E_{acc} (mid-cell)	$[\mathrm{mT/(MV/m)}]$	4.20
E_{pk}/E_{acc} (mid-cell)	[-]	2.26
Cell-to-cell coupling k_{cc}	[%]	3.21
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

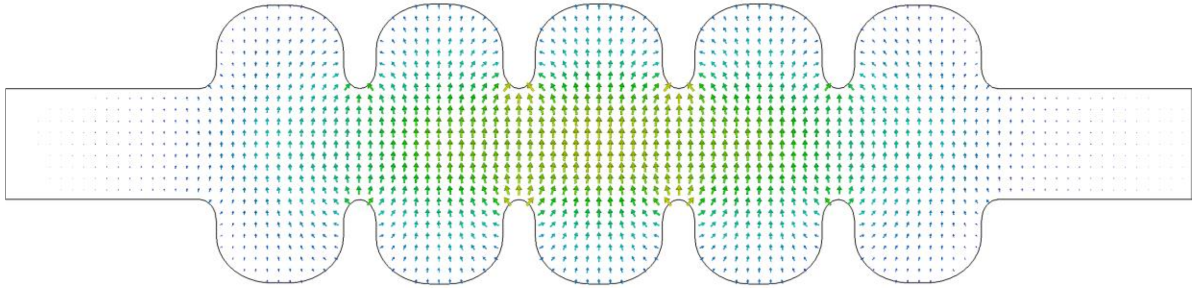
Higher Order Modes

HOM-damping for an ERL is a challenge due to the presence of many turns (undesired losses and multi-bunch beam instabilities)

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

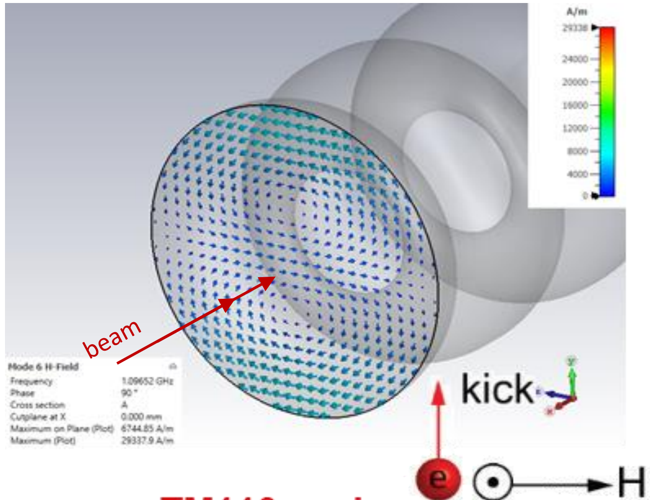


E-field - TE111 mode (Dipole HOM) – f =933.53 MHz



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 (kick)** from its reference orbit: unstable beam motion, transverse emittance growth, beam loss



TM110 mode

HOM numerical simulations (CST Studio Suite® and COMSOL Multiphysics®)

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

Helmholtz equations

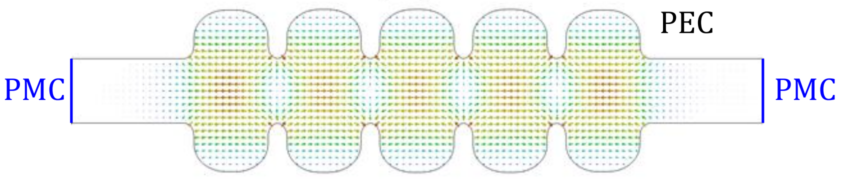
$$\nabla^2\underline{\mathbf{E}} + \omega^2\mu\varepsilon\underline{\mathbf{E}} = 0$$

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

Boundary conditions

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

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



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

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

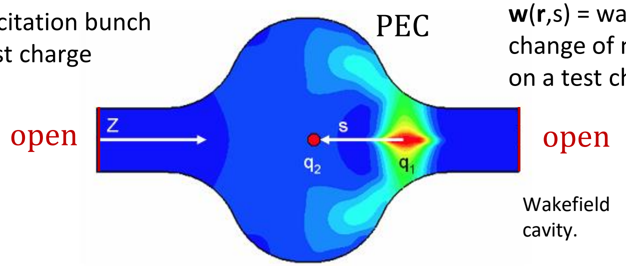
Wake function

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

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



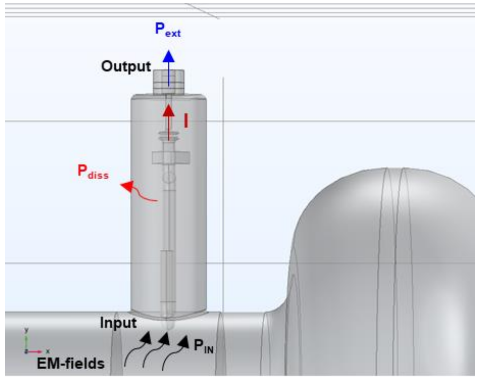
w(**r**,s) = wake function = change of momentum on a test charge q_2

Wakefield in an elliptical cavity.

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

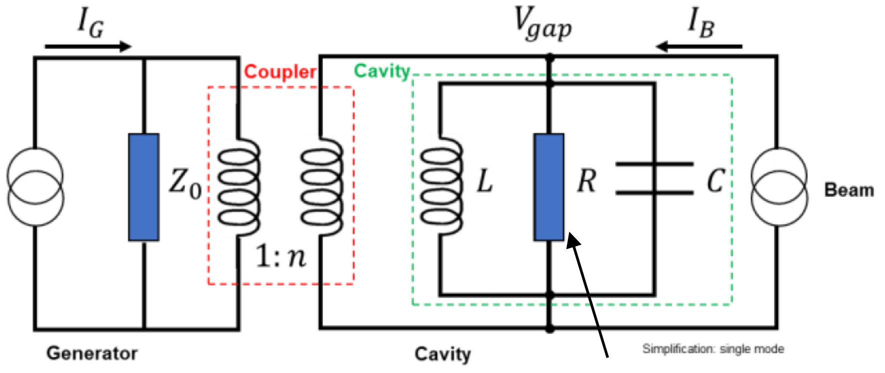
- **BBU analyses**
  - Determine the impedance budget for monopole and dipole modes

- **HOM-coupler power transmission – Frequency domain**
  - Coupler optimization
  - RF-heating studies

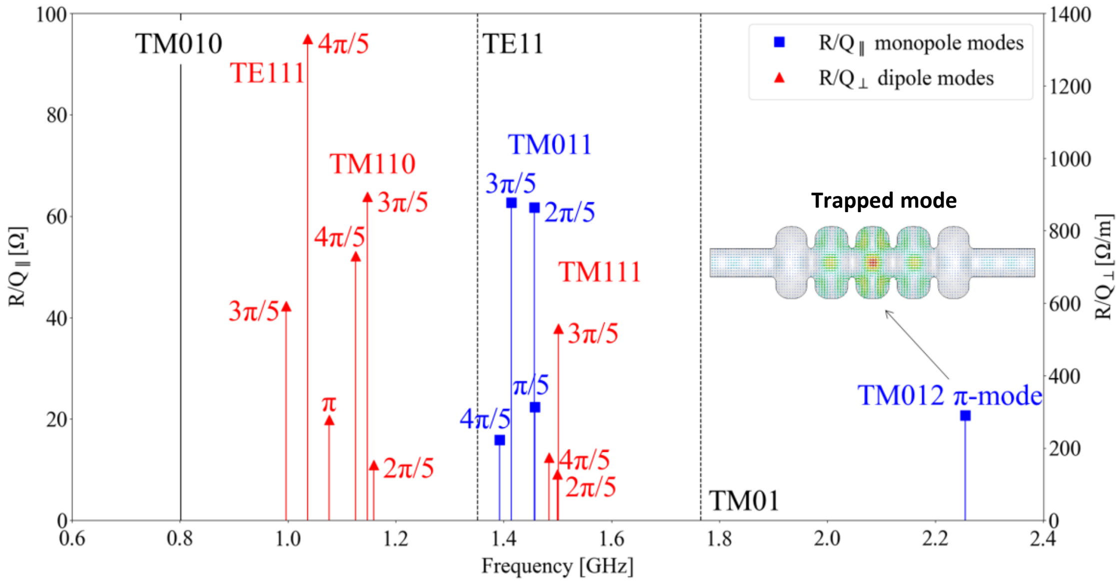


3D-Eigenmode simulation: HOMs identification

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



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



Longitudinal R/Q [Ω]

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

Transverse R/Q [Ω/m]

$$\frac{R}{Q}_{tr,n} = \frac{|V_{l,n}(r=r_0) - V_{l,n}(r=0)|^2}{k r_0^2 \omega_n U_n}$$

Shunt Longitudinal impedance [Ω]

$$R_l = \frac{R}{Q}_{l,n} \cdot Q_L$$

Shunt Transverse impedance [Ω/m]

$$R_{tr} = \frac{R}{Q}_{tr,n} \cdot Q_L$$

- **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)

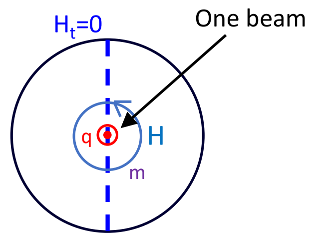
- Damping HOMs means reducing the **shunt impedance**, having a low loaded quality factor Q_L (in SRF cavities $Q_L \approx Q_{ext}$)

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

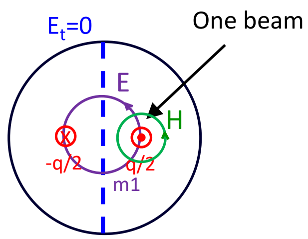
$$\frac{1}{Q_L} = \frac{P_{loss}}{\omega_n U_n} = \frac{P_{cav} + P_{ext,1} + P_{ext,2} + \cdots}{\omega_n U_n}$$

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

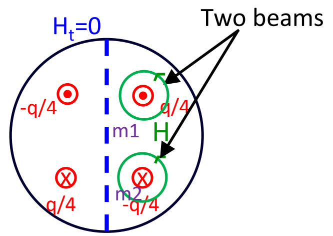
- The implemented method allows to excite separately monopole, and dipole modes, suppressing unwanted modes [2].



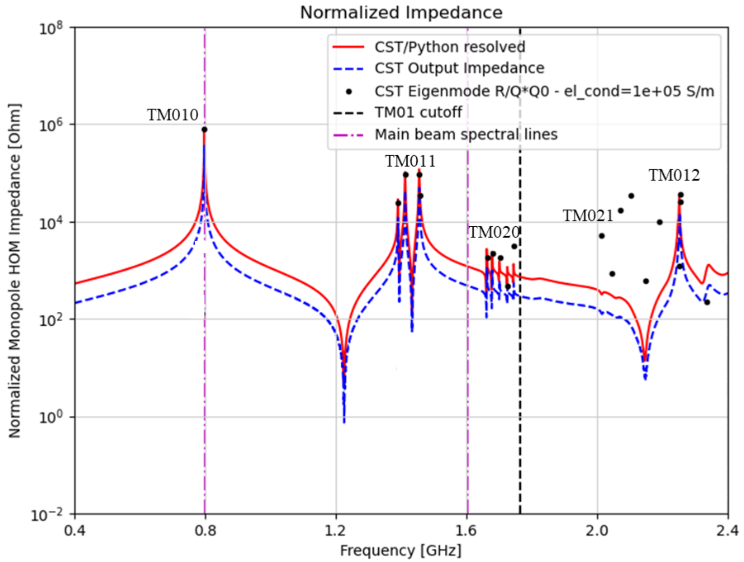
Monopole modes

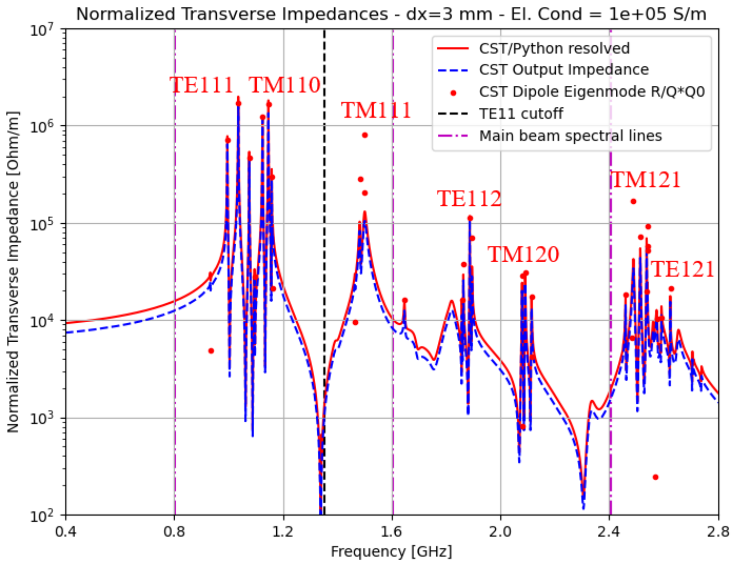


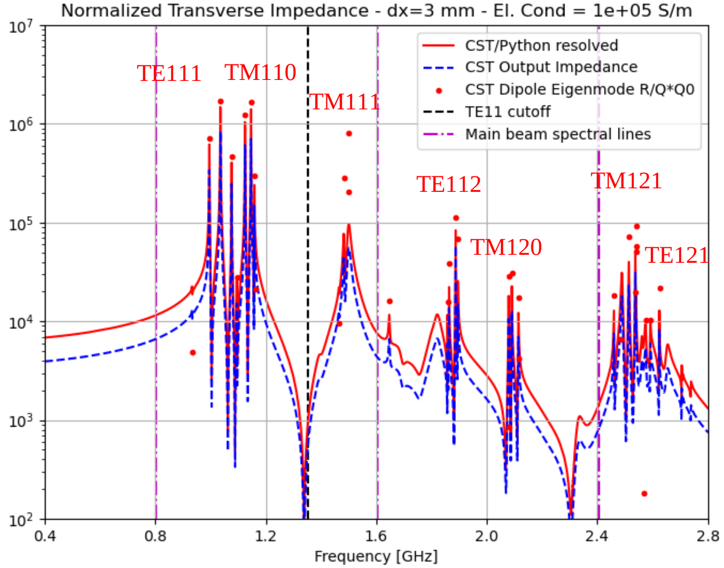
Dipole modes – polar 1



Dipole modes – polar 2







Longitudinal wake impedance [Ω]

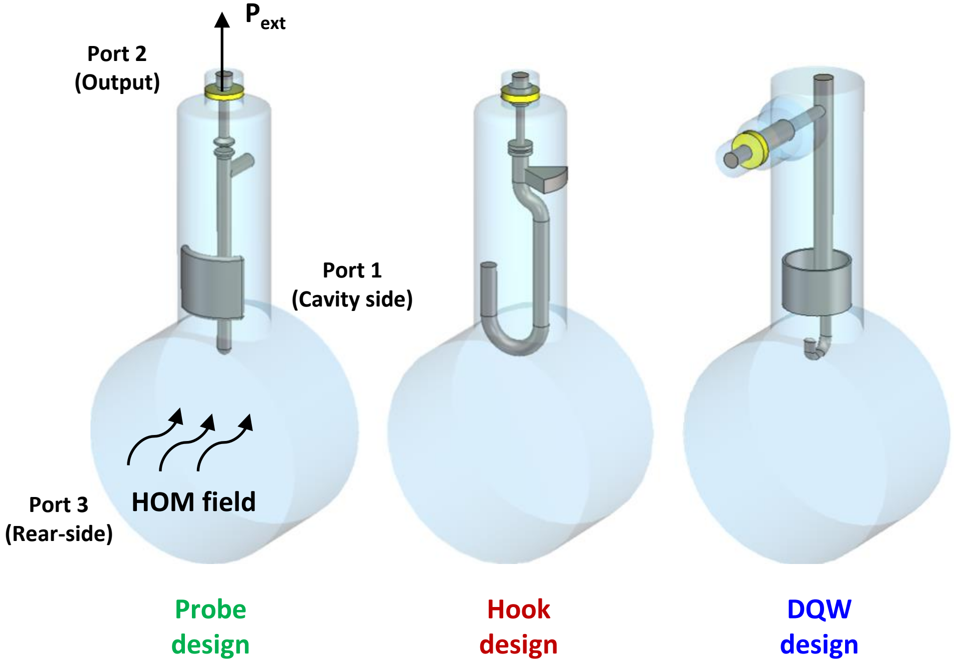
$$Z_{||}(\mathbf{r},\omega) = \frac{1}{c}\int_{-\infty}^{\infty} w_{||}(\mathbf{r},s)\, e^{-\frac{j\omega s}{c}} ds$$

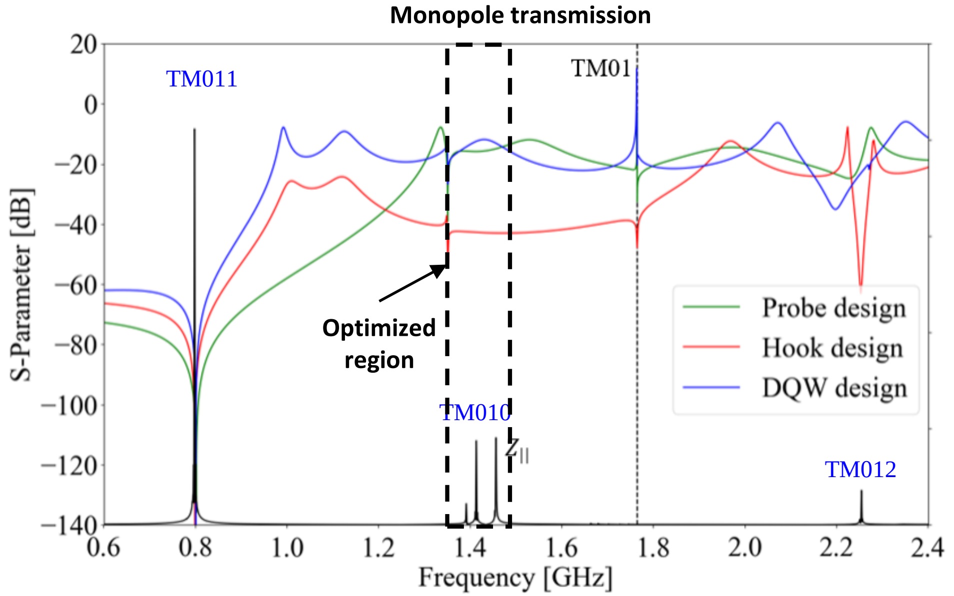
Transverse wake impedance [Ω/m] – Panofsky-Wenzel Theorem

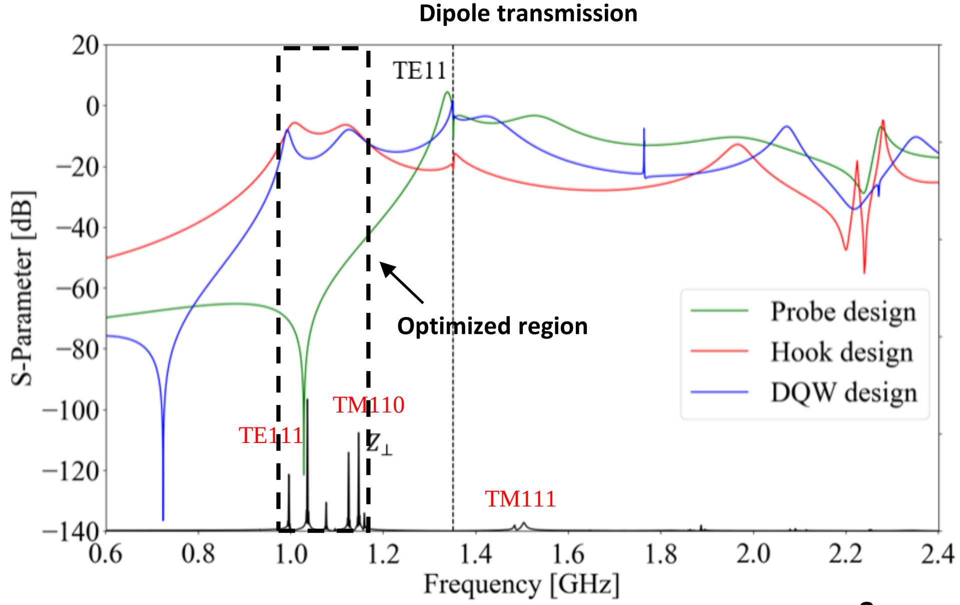
$$\boldsymbol{Z}_{\perp}(\mathbf{r},\omega) = \frac{j\beta c}{\omega_n r_0}\nabla_{\perp} Z_{||}(\mathbf{r},\omega)$$

- 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) [3]

HOM coupler optimization



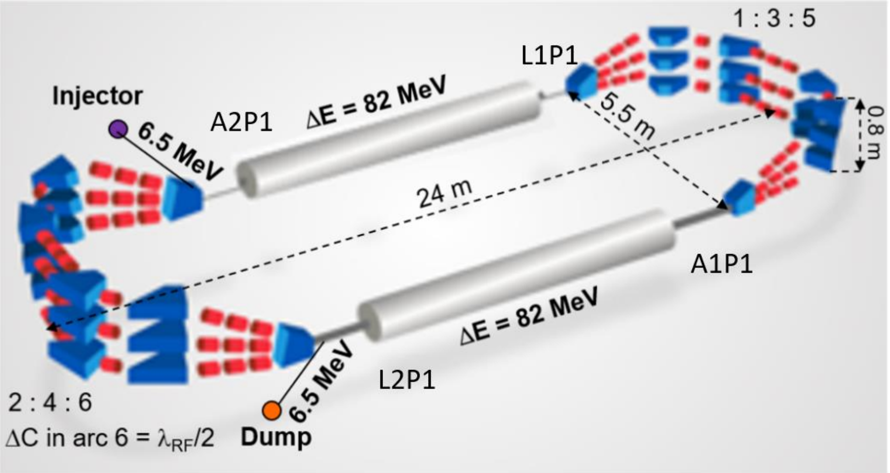




- HOM couplers are geometrically optimized according to the HOM spectrum ($Z_{||}$ and $Z_{\perp}$)
- The S-parameters between the beam pipe port 1 and port 2 at the coaxial output of the coupler are studied.

- The DQW coupler exhibits a better monopole coupling for TM010 mode than the probe design.
- The hook coupler provides higher damping of the first two dipole passbands (TE111 and TM110)

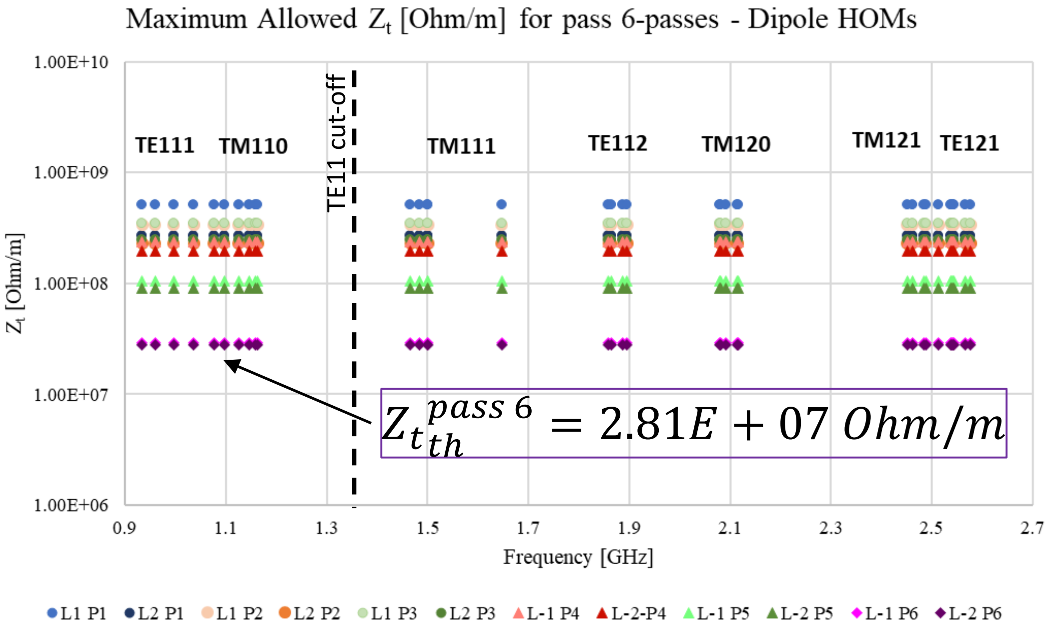
BBU analyses

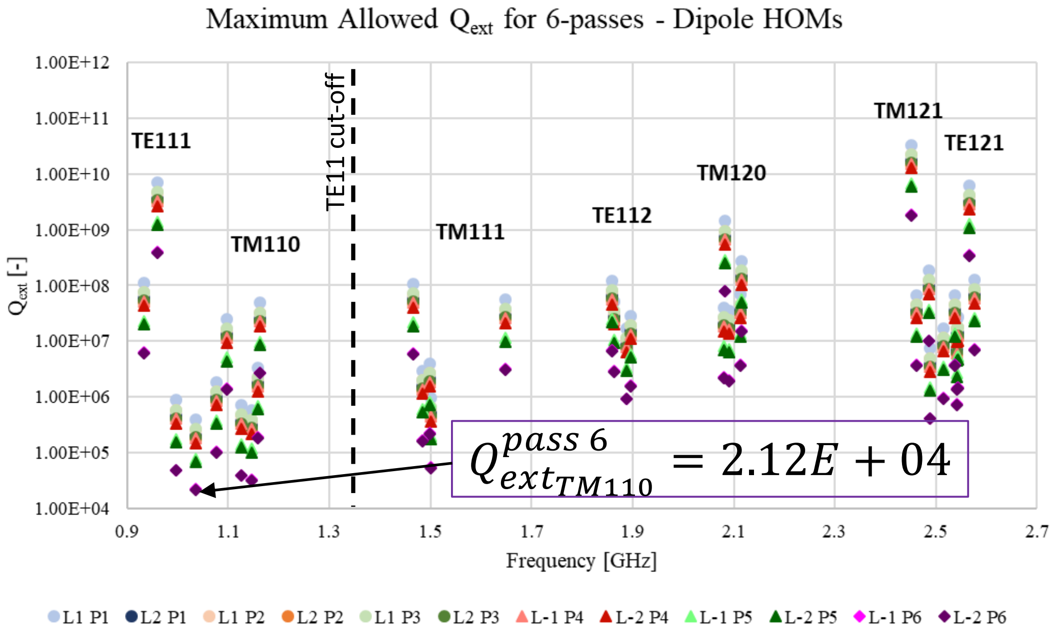


Threshold current for a single dipole HOM for the jth-pass in a multi-pass machine [4]*:

$$I_{th\,j} = \frac{-2p_j c}{ek\left(\frac{R}{Q}\right) Q \sum_{j=1}^{N}\left(M_{12}^{L1,j}\cdot\frac{p_{in}^{L1,j}}{p_{out}^{L1,j}} + M_{11}^{A1,j} + M_{12}^{L2,j}\cdot\frac{p_{in}^{L2,j}}{p_{out}^{L2,j}} + M_{11}^{A2,j}\right)}$$

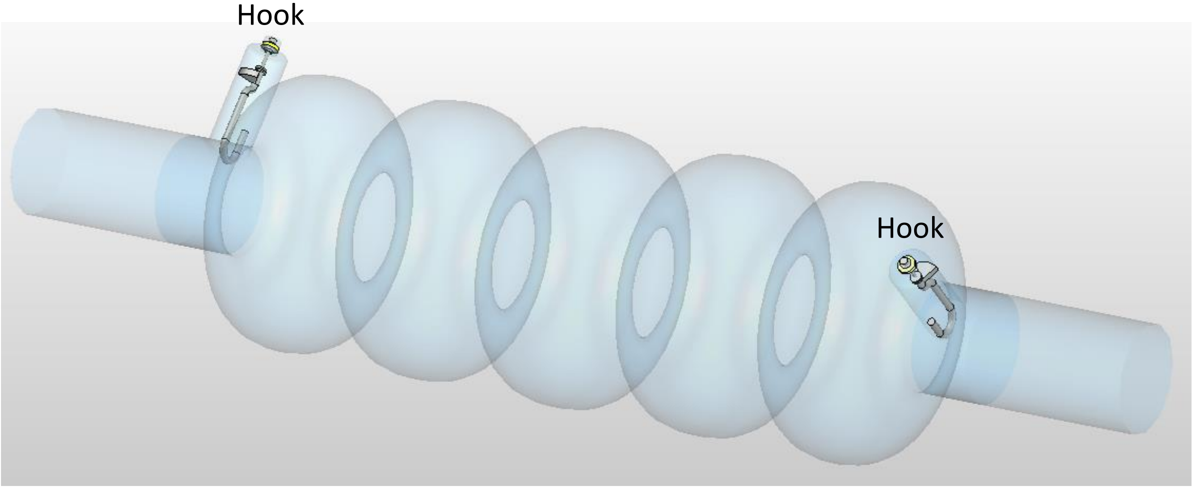
Supposing a beam current of 120 mA (PERLE total current), we can calculate the maximum allowed Q_{ext} to avoid beam instabilities as well as the impedance budget



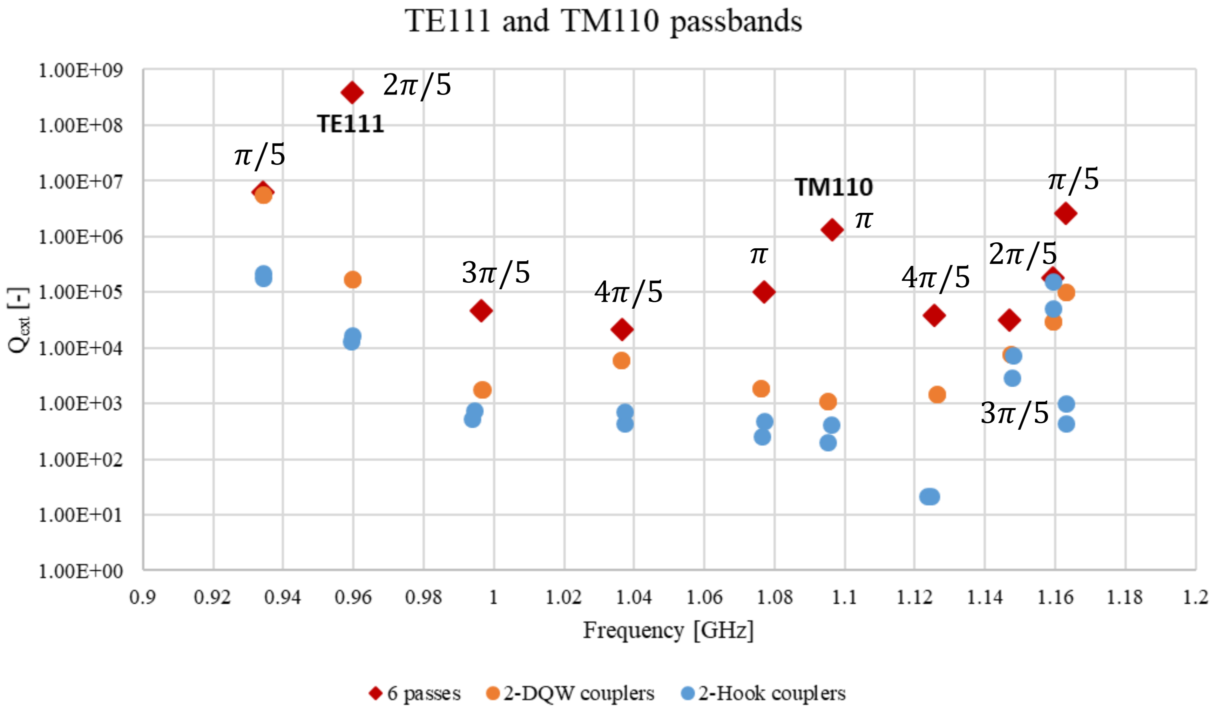


*Transfer matrices were provided by Dr. Sadiq Setiniyaz and Dr. Robert Apsimon, Lancaster University & Cockcroft Institute, Daresbury Laboratory.

Q_{ext} evaluation for a 2-HOM coupler scheme



- 2 Hook couplers (one coupler per side), rotated by 90° to coupler both dipole polarizations
- Compute the Q_{ext} at the coupler port for the excited dipole HOMs
- Compare the obtained Q_{ext} with the maximum allowed Q_{ext} from BBU analyses

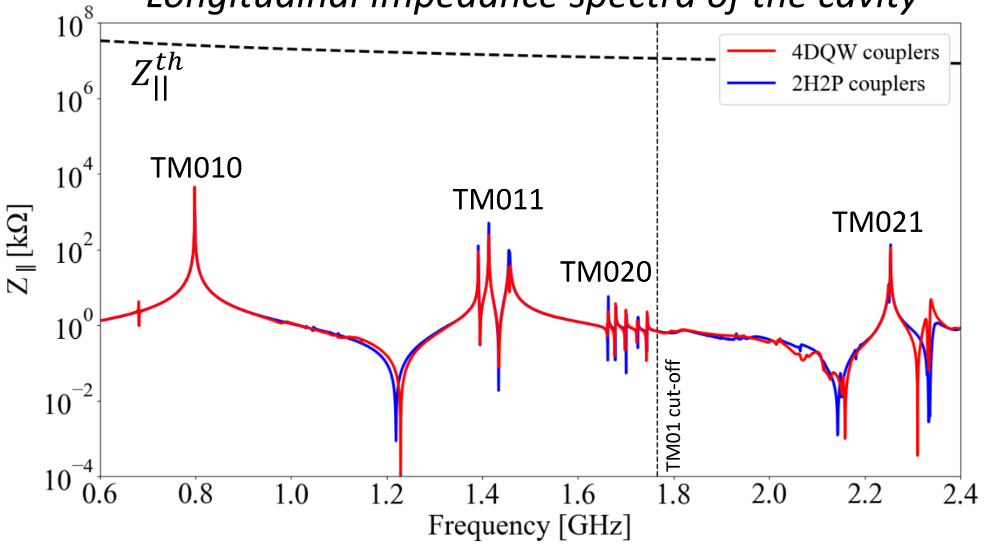


- In general, the 2-Hook coupler scheme couples better TE111 and TM110 passbands than the 2-DQW coupler scheme
- 2-Hook scheme shows a Q_{ext} comparable to that one obtained in BBU analyses for the $2\pi/5$ TM110 mode
- 2-DQW scheme shows a Q_{ext} comparable to that one obtained in BBU analyses for the $\pi/5$ TE111 mode

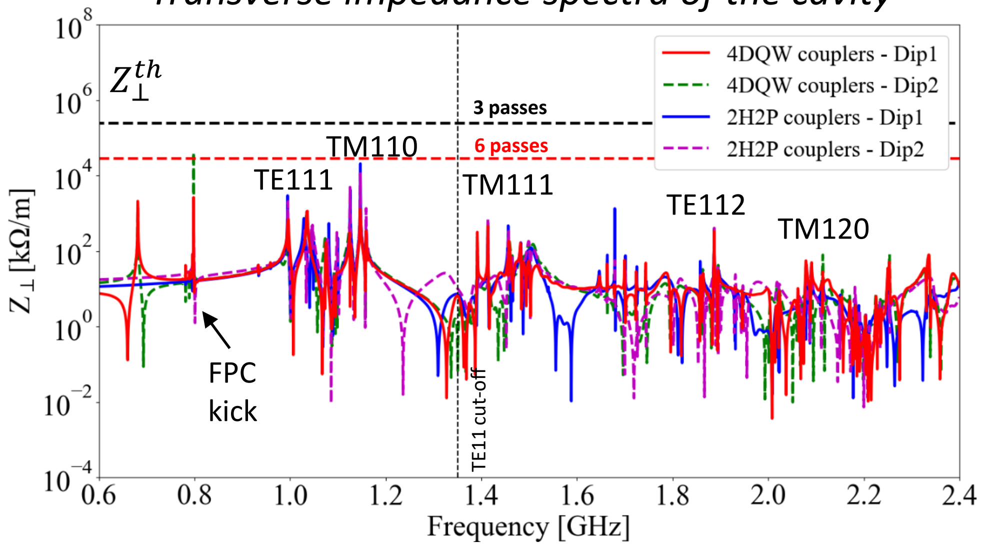
HOM-damping schemes (5-cell cavity + HOM couplers)

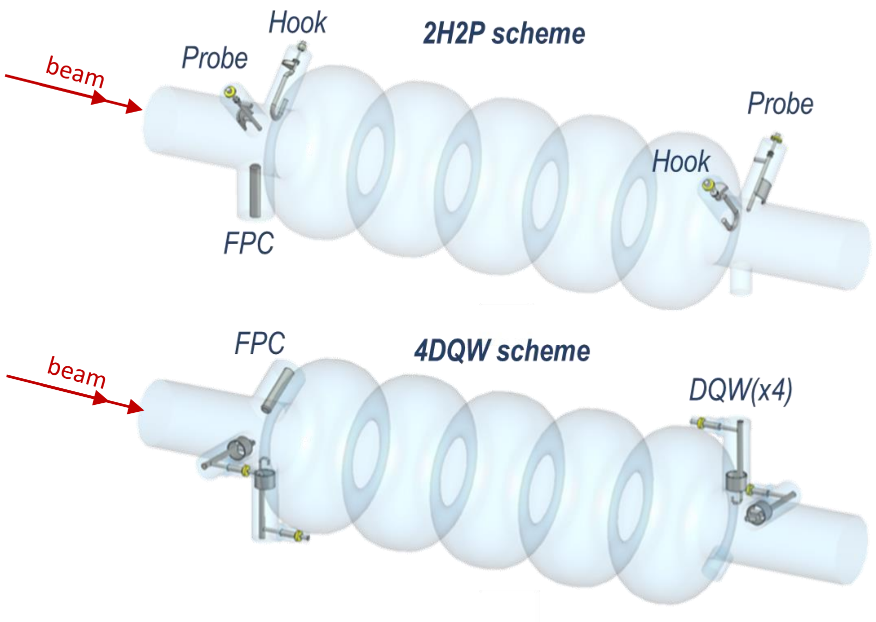
- **Objective**: extract the energy of the dangerous HOMs from the cavity through HOM couplers.

Longitudinal impedance spectra of the cavity



Transverse impedance spectra of the cavity

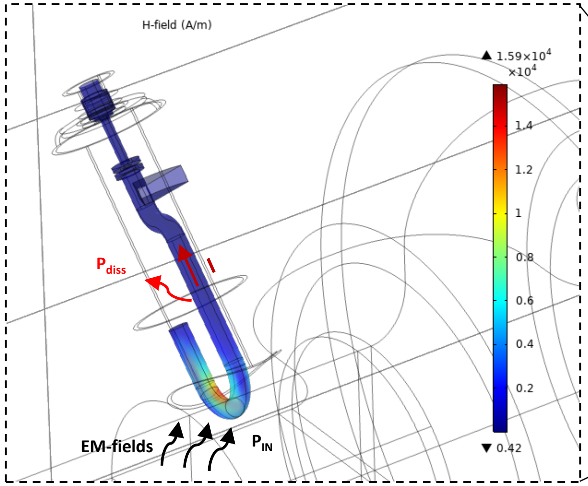




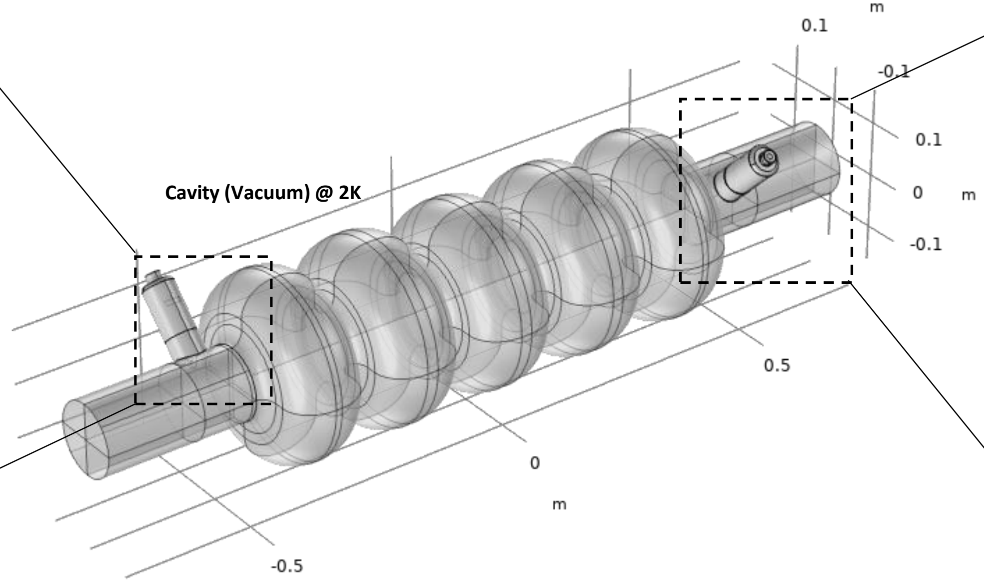
- The damping scheme with four DQW couplers shows promising results in damping both monopole and dipole HOMs
- Computed impedance levels are below the analytically-computed beam-stability limits for both configurations, however very low margin for TM110 mode in 2H2P configuration.

RF-Heating Analysis (COMSOL Multiphysics®) – Fundamental Mode

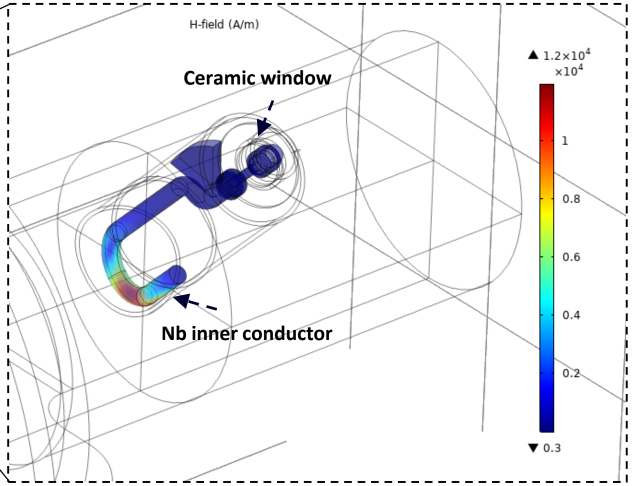
H-field [A/m] – TM010 mode



$$B_{FM_{max}} = \mu_0 H_{FM} = 20\ mT$$

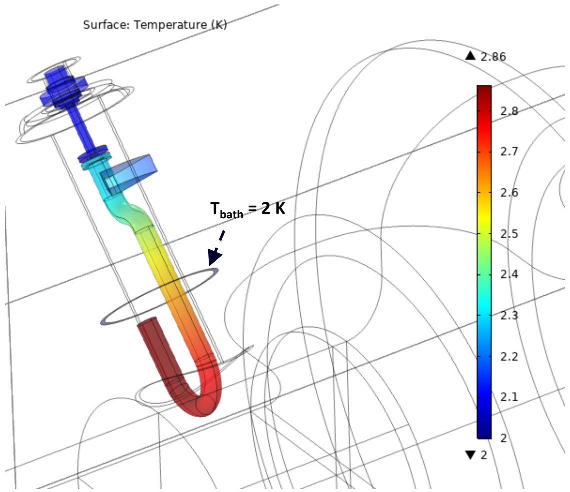


H-field [A/m] – TM010 mode



$$B_{FM_{max}} = \mu_0 H_{FM} = 15\ mT$$

Temperature [K] – TM010 mode



$$T_{max} = 2.86\ K$$

- Electric surface current for the i^th HOM

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

- Power dissipation on the conductor

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

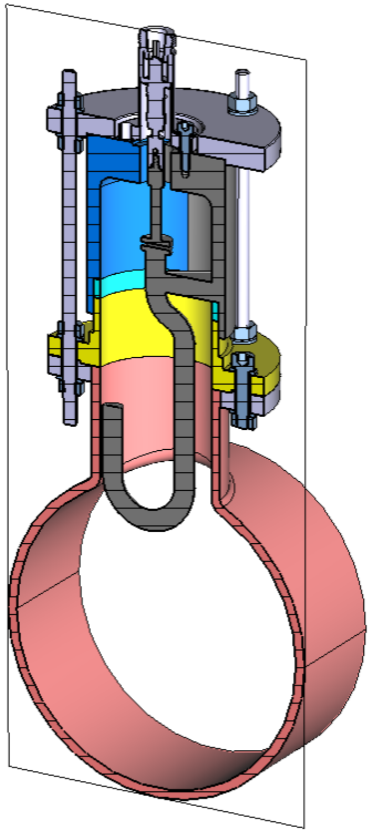
- Evaluation of the maximum temperature

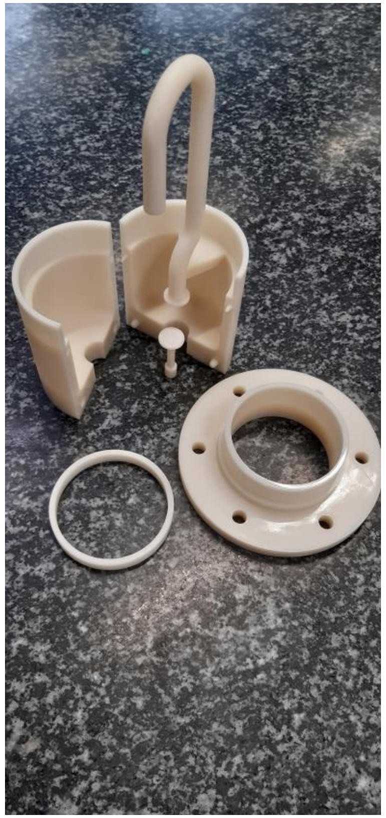
	E_{pk} [MV/m]	B_{pk} [mT]
Hook-coupler	19.63	21.22
Probe-coupler	34.30	31.83
DQW-coupler	45.13	70.27

	$P_{diss-inner}$ [mW]	$P_{diss-outer}$ [mW]	T_{max} [K]
Hook-coupler	3.21	1.57	2.86
Probe-coupler	5.02	1.99	3.03
DQW-coupler	38.11	2.13	4.41

HOM coupler fabrication

- Mechanical design of the Hook coupler for the PERLE cavity has been made at IJCLab (Samuel Roset, Patricia Duchesne, Gilles Olivier, Guillaume Olry - IJCLab)
- The coupler has been 3D printed in epoxy by CERN Geneva Polimer Lab, and it will be copper coated (Sébastien Clement, Simon Barriere, Pierre Maurin, Romain Gerard)





- The coupler will be installed next week at JLab on a 1-cell 801.58 MHz copper elliptical cavity to test HOM coupler performance.

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.
- An analytical formulation to calculate the threshold current for a single dipole HOM for the j^{th}-pass in a multi-pass ERL was developed.
- HOM-damping scheme studies: 4 DQW couplers seem to provide better damping than 2 Hook + 2 Probe couplers configuration both for dipole and monopole HOMs. Computed impedance levels are below the analytically-computed beam-stability limits.
- RF-heating analyses were performed on the HOM couplers. The highest field and temperature were detected on the antenna of the DQW coupler.
- The first mechanical design of the Hook coupler has been made, and it has already been fabricated in additive manufacturing (epoxy + copper coating)

Future studies:

- Experimental tests on Q4 2022 and Q1 2023 of a 1-cell and 5-cell 801.58 MHz copper cavity at JLab to test the fabricated HOM couplers
- Simulate beam stability thresholds for longitudinal and transverse impedance through tracking codes
- RF-heating analyses of HOM coupler antenna for the HOMs, and evaluate if an active cooling of the antenna is required.

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- University of Wismar: Kai Papke

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References

[1] F. Marhauser *et al.*, "Recent results on a multi-cell 802 MHz bulk Nb cavity", presented at the *FCC week 2018*, Amsterdam, Netherlands, 2018.
[2] 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.
[3] 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.
[4] 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.

Thank you for your attention!

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