HOM Coupler Prototyping and Measurements for the SRF Cavity for PERLE

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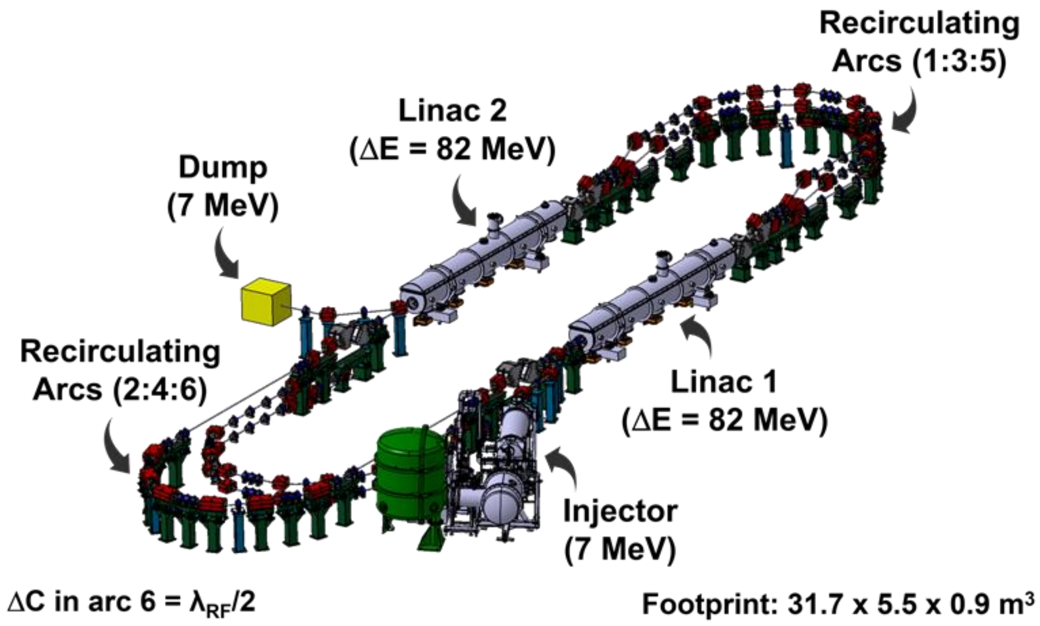
PERLE Collaboration Meeting

CERN, Geneva, Switzerland, January 23 – February 3, 2023

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)



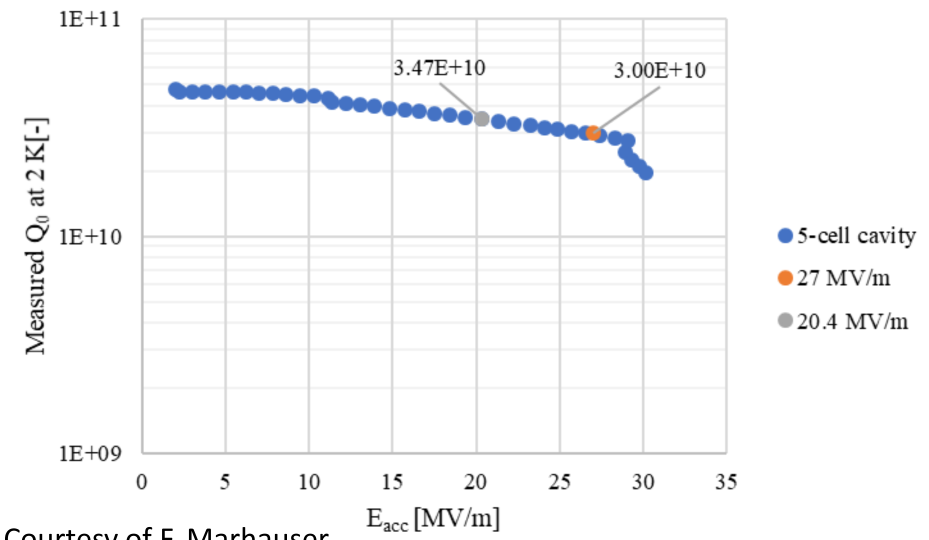
Target Parameter	Unit	Value
Injection energy	MeV	7
Electron beam energy	MeV	500
Normalized Emittance $\Upsilon\varepsilon_{x,y}$	mm·mrad	6
Total average beam current	mA	120
Bunch charge	pC	500
Bunch length	mm	3
Bunch spacing	ns	25
RF frequency	MHz	801.58
Duty factor	CW (Continuous Wave)	

- 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

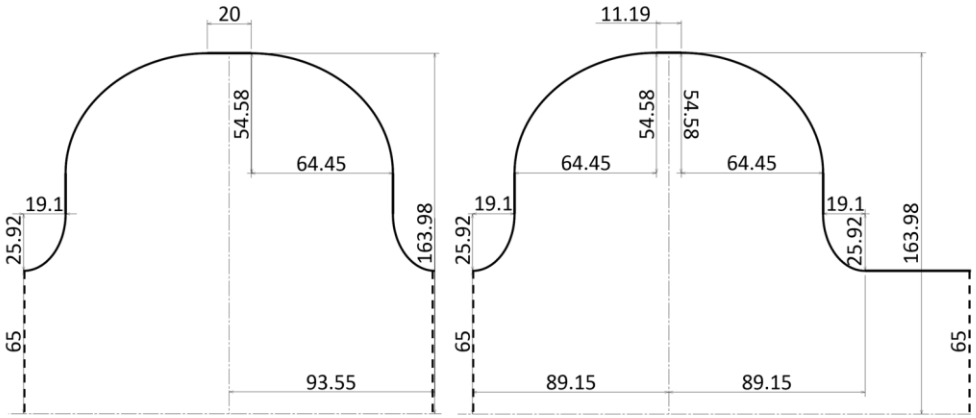
The first 801.58 MHz 5-cell elliptical Nb cavity has already been fabricated and successfully tested at JLab in October 2017 [1].

Courtesy of F. Marhauser



Courtesy of F. Marhauser

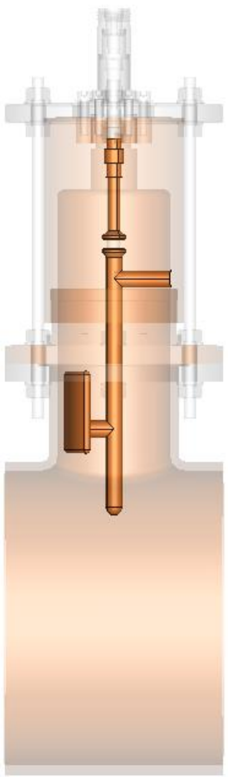
Cavity Parameters	Unit	Value
Frequency	[MHz]	801.58
Temperature	[K]	2.0
Cavity active length	[mm]	917.9
R/Q	[Ω]	523.9
Q_0 at 2 K (E_{acc}=20.4 MV/m)	[-]	3.74E+10
Geometry Factor (G)	[Ω]	274.6
B_{pk}/E_{acc} (mid-cell)	[mT/(MV/m)]	4.20
E_{pk}/E_{acc} (mid-cell)	[-]	2.26
Cell-to-cell coupling k_{cc}	[%]	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



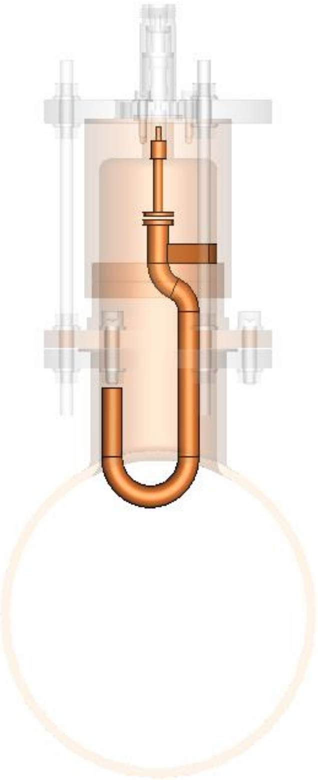
Mid-cell End-cell

HOM Coupler design

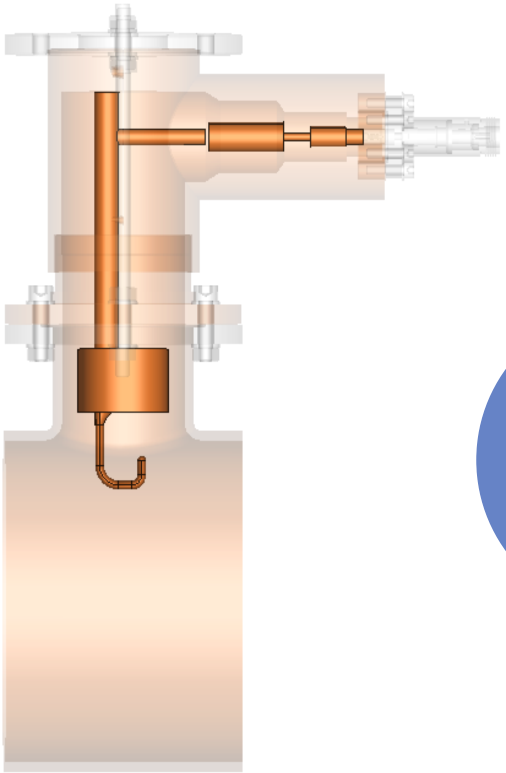
Number of factors have to be considered: RF transmission behavior, BBU instabilities, power dissipation and heat loss, mechanical design, materials for prototyping couplers, real performances (RF measurements)



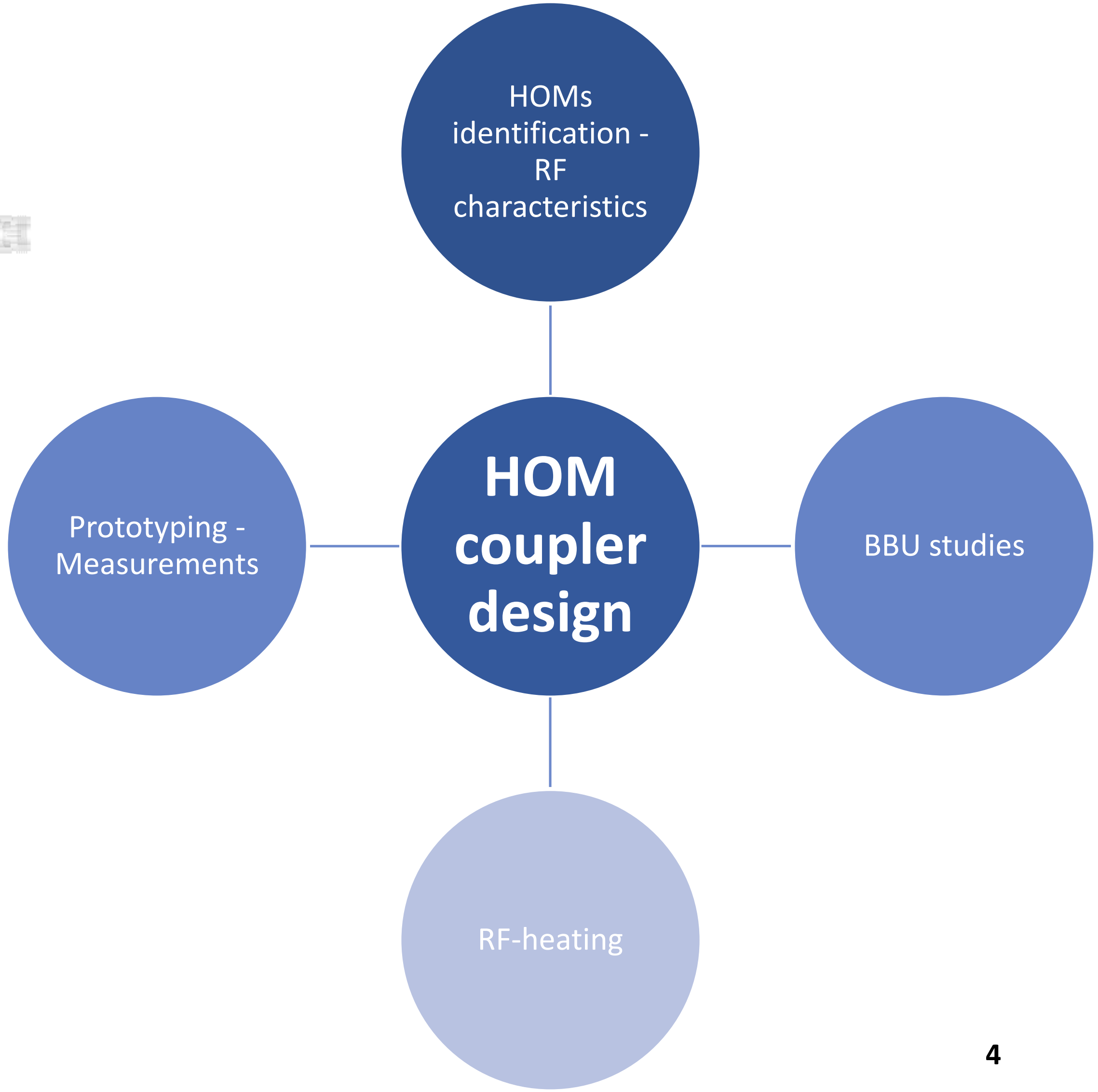
Probe design



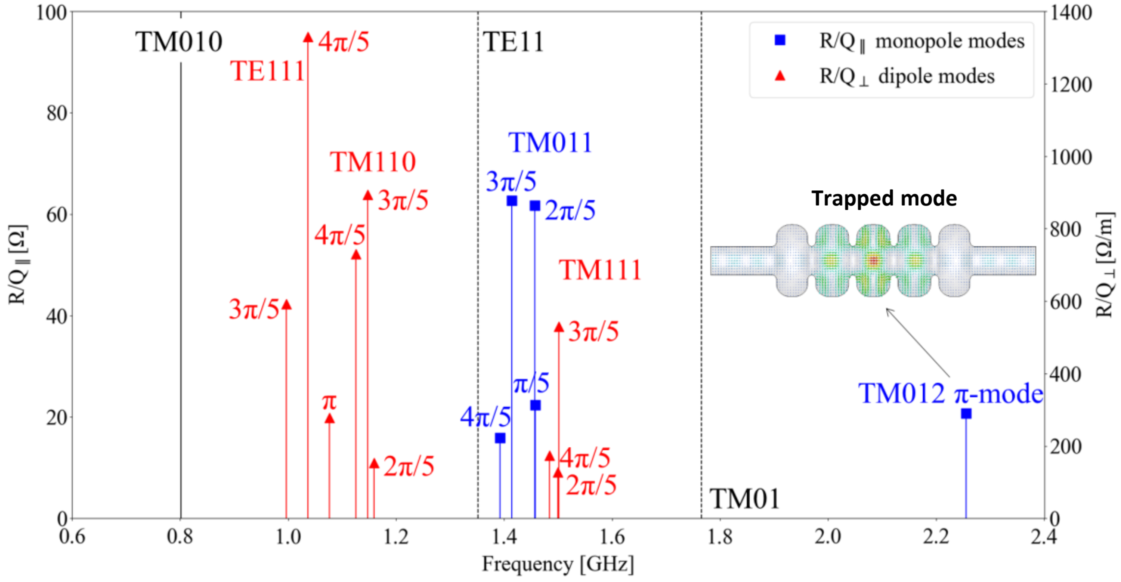
Hook design

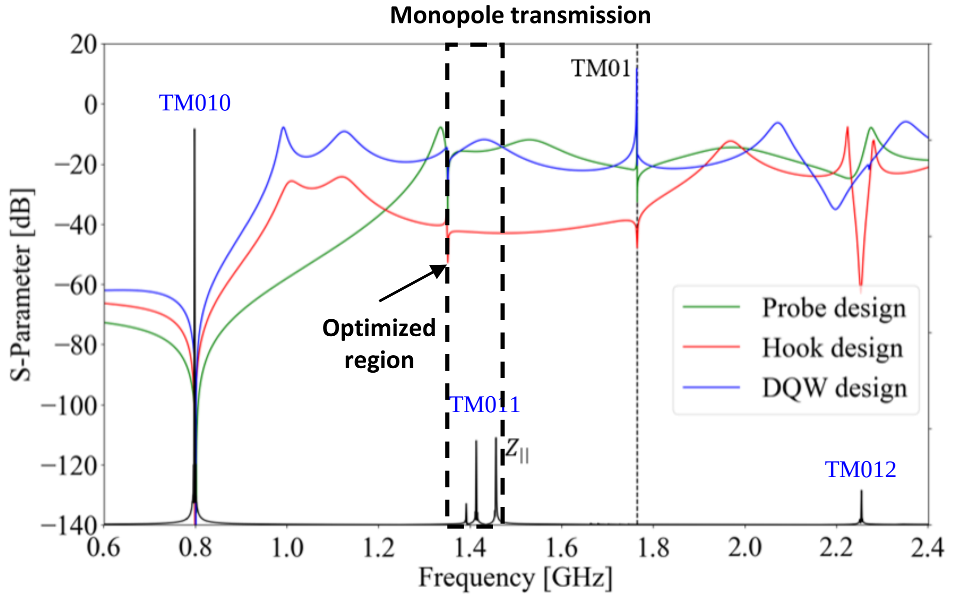


DQW design



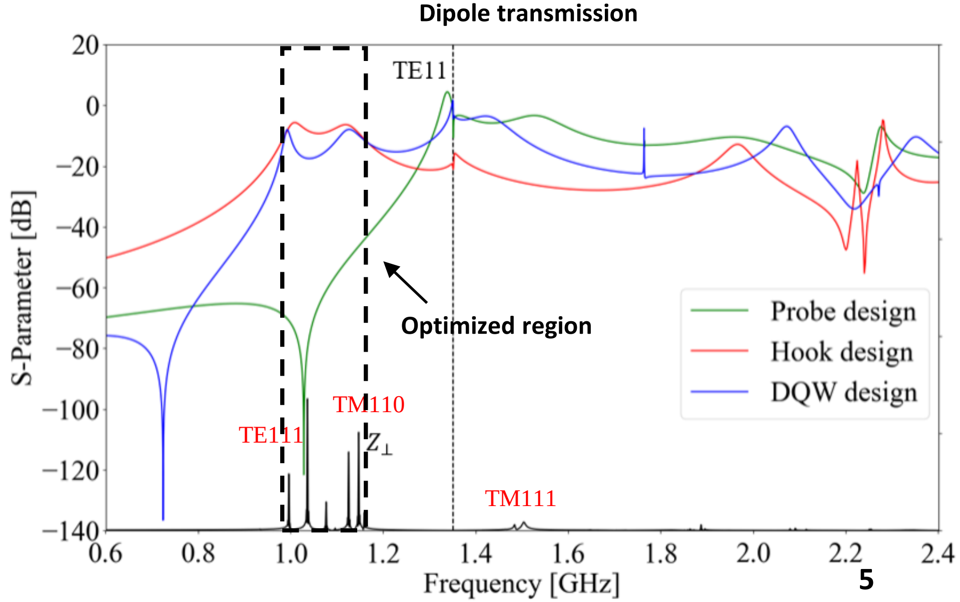
HOMs identification and RF characteristics of HOM couplers





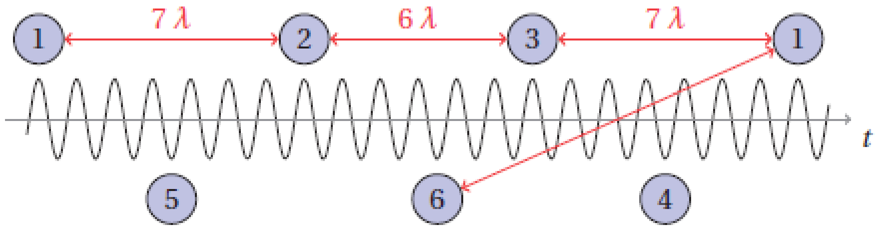
- Identification of the high-R/Q modes
- Optimization of HOM coupler geometry to maximize S-parameter transmission according to the HOM spectrum ($Z_{||}$ and $Z_{\perp}$)

- The DQW coupler exhibits a better monopole coupling for the TM011 mode passband than the probe design.
- The Hook coupler provides higher damping of the first two dipole passbands (TE111 and TM110)



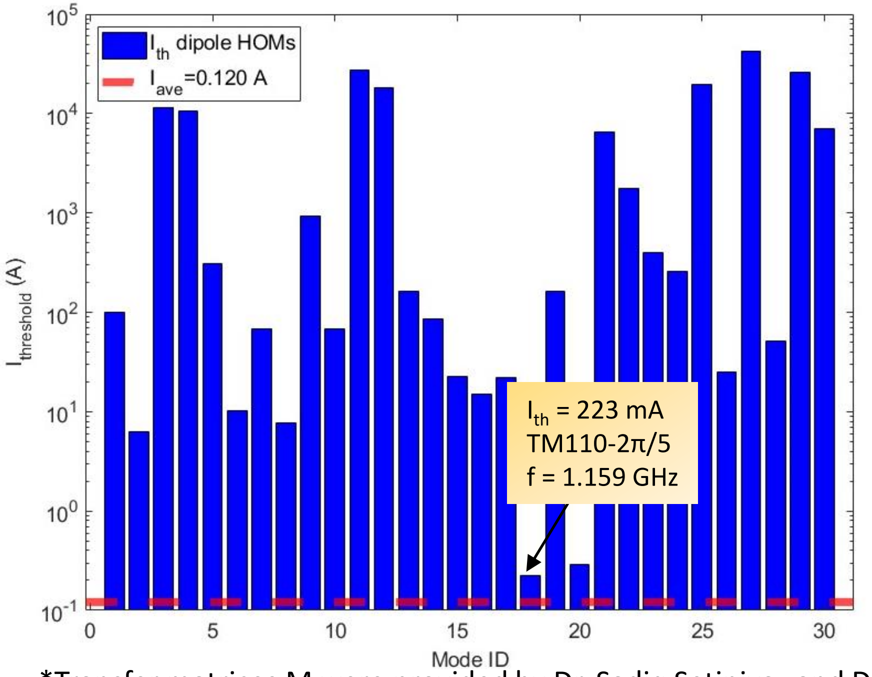
Multi-pass Beam Breakup (BBU)

Courtesy of D. Pellegrini



PERLE recombination pattern

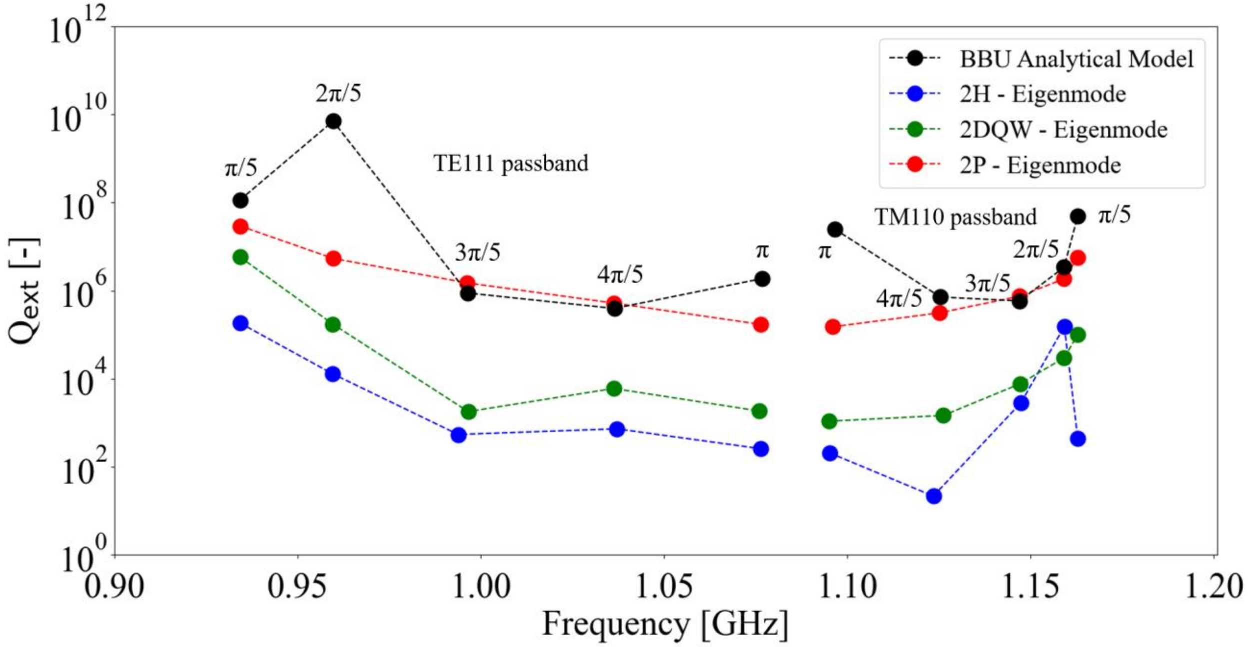
Threshold current for a single HOM (2H2P coupler scheme)



Multi-pass machine analytical model (single HOM)

$$I_{th\,j} = -\frac{2E}{e\left(\frac{R}{Q}\right)_\lambda Q_\lambda k_\lambda \sum_{j>i=1}^{N_c}\left(\frac{E}{E_j}\right)(M^{ij})_{mn}\sin(\omega_\lambda t_r^{ij})}$$

- Estimating the maximum allowed Q_{ext} to avoid beam instabilities for the worst monopole (m=5, n=6) and dipole (m=1,3; n=2,4) HOMs for I_0 = 120 mA.
- Estimation of impedance budget and current threshold I_{th} for each HOM
- Particle tracking simulations are needed to take into account multiple HOMs
- PLACET2 predicted 250-260 mA for the TM110-2π/5 (K. André, CERN)

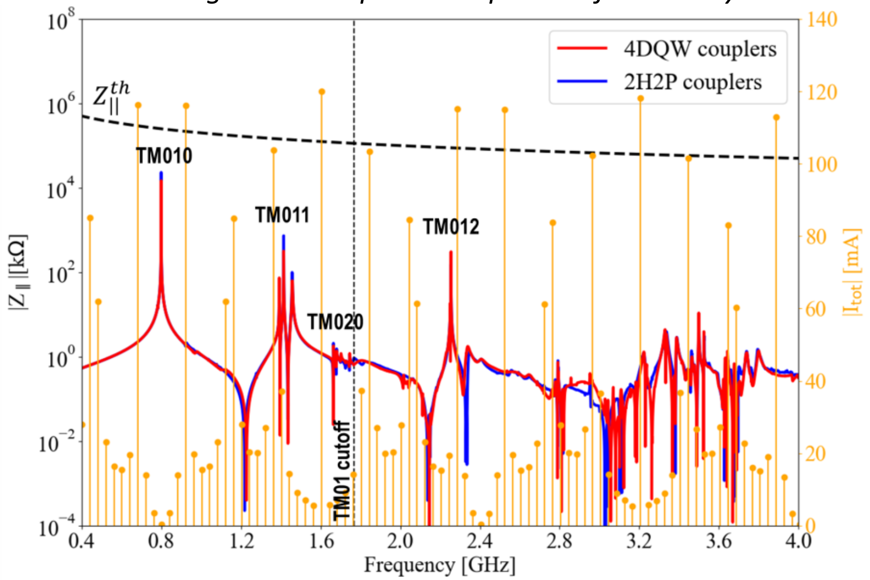


*Transfer matrices M were provided by Dr. Sadiq Setiniyaz and Dr. Robert Apsimon, Lancaster University & Cockcroft Institute, Daresbury Laboratory.

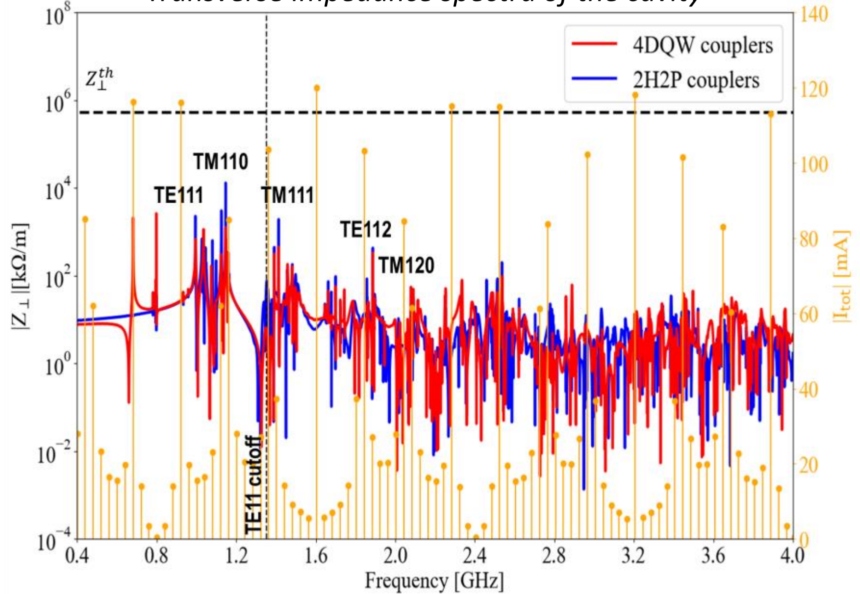
HOM-damping schemes (5-cell cavity + HOM couplers)

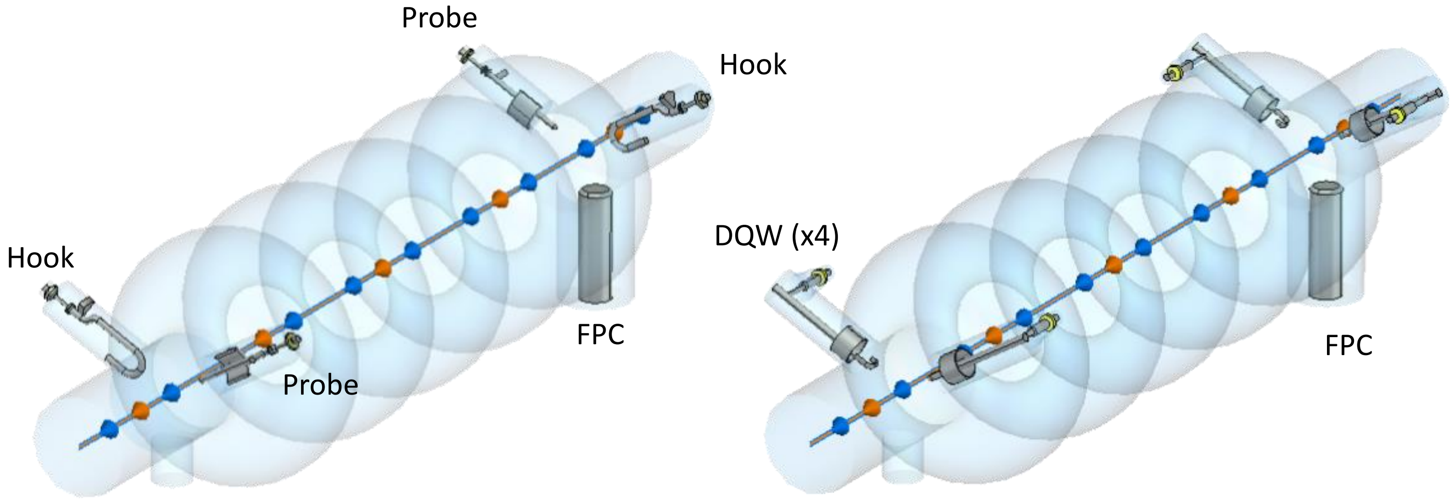
- **Objective**: extract the energy of the dangerous HOMs from the cavity through HOM couplers.

Longitudinal impedance spectra of the cavity



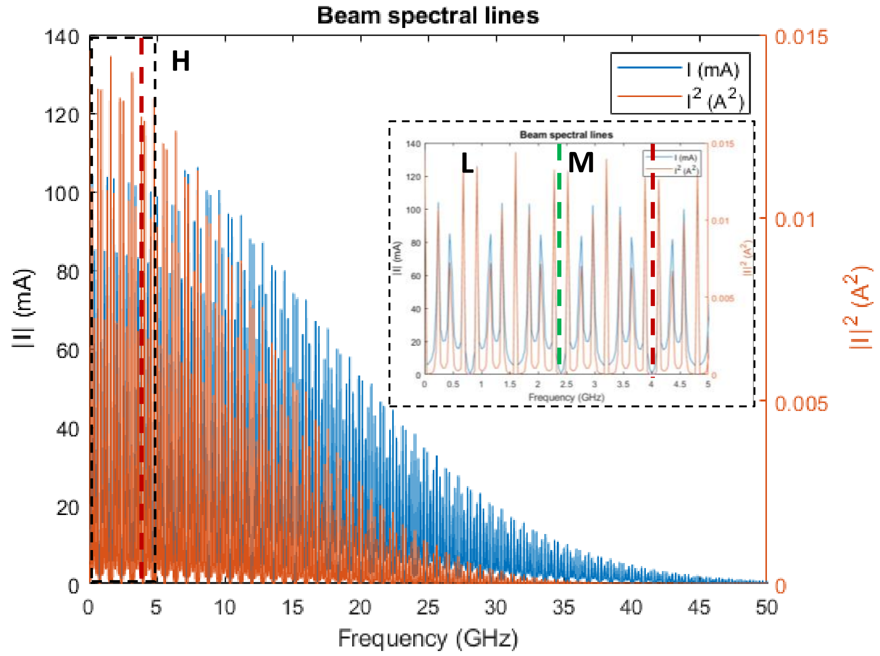
Transverse impedance spectra of the cavity





- 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 the analyzed configurations.

HOM Power Deposition (5-cell cavity + HOM couplers)



- Beam-induced HOM power:

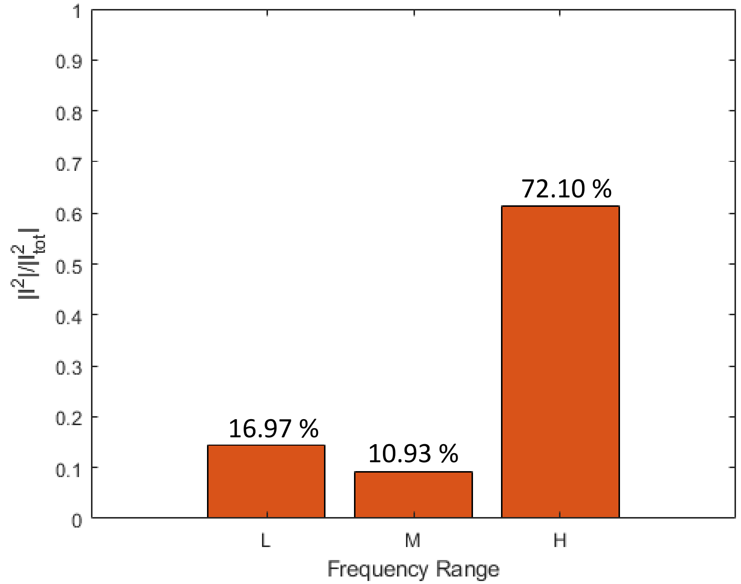
$$P = I_{ave}^2 \sum_{k=-\infty}^{+\infty} \mathrm{Re}\,[Z_{||}(k\omega_0)]\left|\hat{I}_k\right|^2 \qquad P_{tot} \approx P_L + P_M + \frac{72.10}{10.93} P_M$$

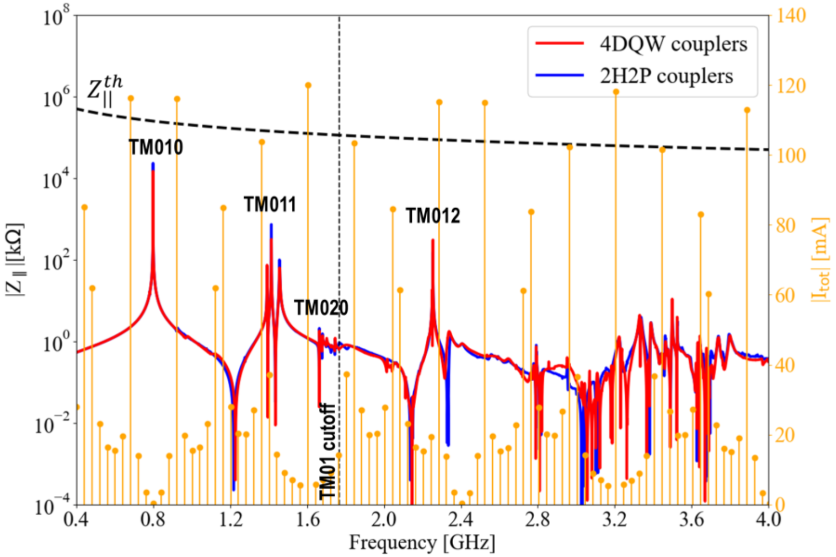
- Beam-induced average HOM power:

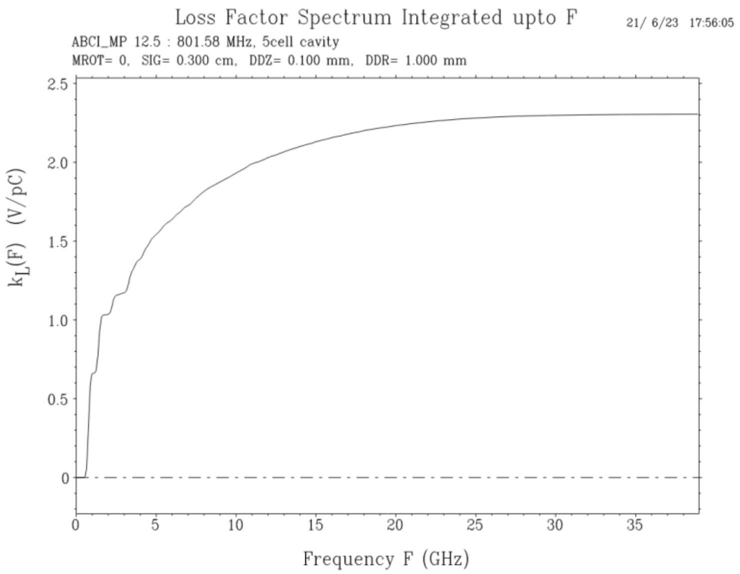
$$P_{ave} = k_{||} Q_b I_{ave} = 103.20\ \mathrm{W} \qquad P_{ave_L} = 33.34\ \mathrm{W} \qquad P_{ave_{M+H}} = 69.86\ \mathrm{W}$$

HOM Power Propagating Through Ports

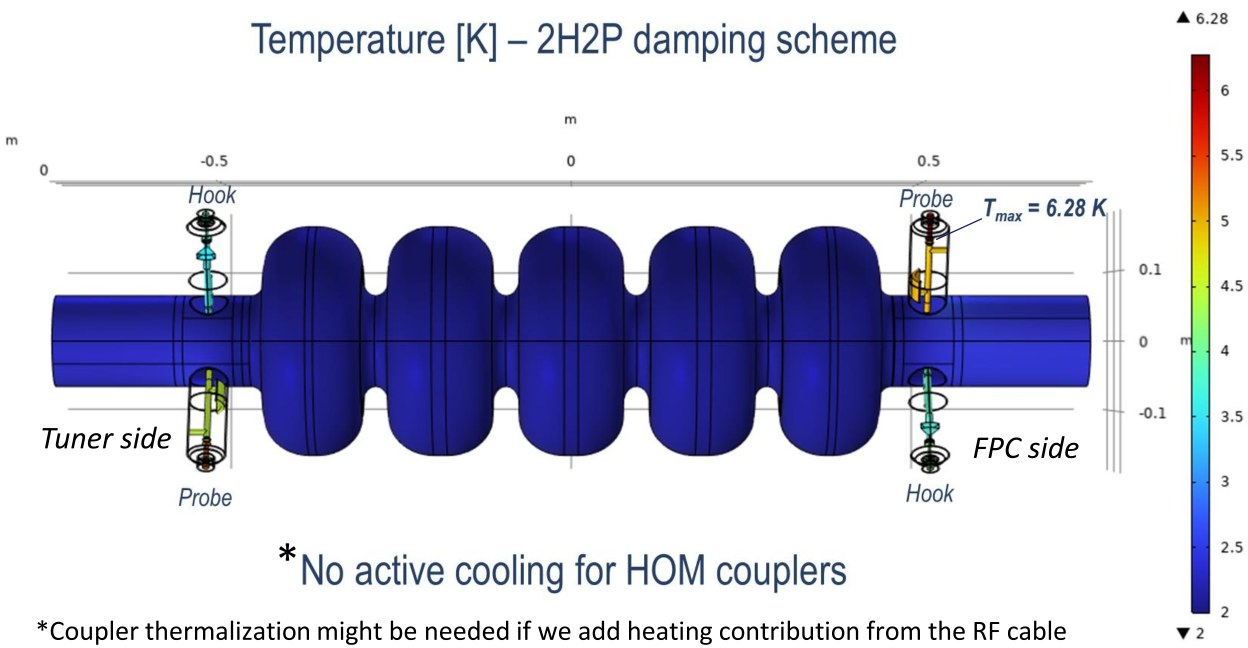
	P_L^* [W]	P_M^* [W]	P_H^* [W]	P_{tot}^* [W]	BPs [%]	FPC [%]	Hooks [%]	Probes [%]	DQWs [%]
2H2P	5.66	9.16	60.39	75.21	82.17	10.49	2.57	4.77	-
4DQW	4.20	7.97	52.57	64.74	76.71	14.40	-	-	8.89



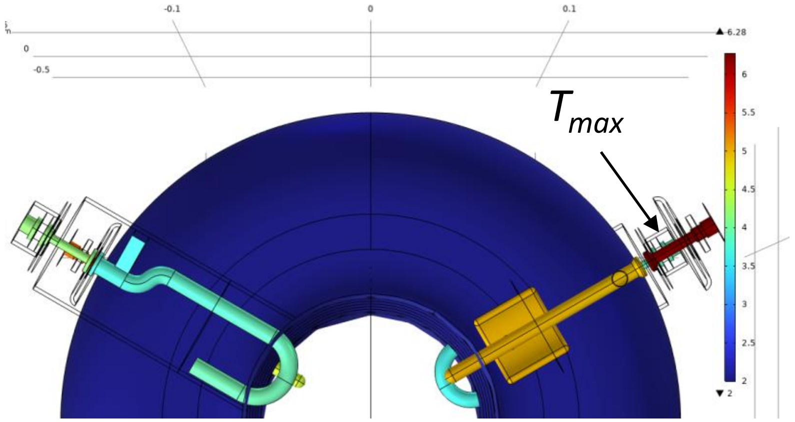




RF-Heating Analysis – Dynamic load



*Coupler thermalization might be needed if we add heating contribution from the RF cable



T_{max}=6.28 K (Probe coupler's upper antenna - FPC side) if no-active cooling is applied to the HOM couplers ($T_{c,Nb}$=9.2 K)

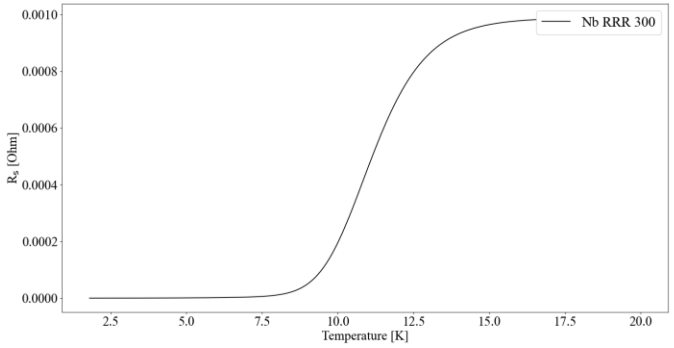
- Total local heat flow on the coupler surfaces

$$\frac{\partial P_{ds}}{\partial A} \approx \frac{1}{2} R_s(T, f_0) \sum_{i=0}^{N} \left(\frac{\omega_i}{\omega_0}\right)^2 \boldsymbol{H_i} \cdot \boldsymbol{H_i^*}$$

- RF surface resistance

$$R_s = R_{BCS}(f, T, RRR) + R_{res}$$

$R_s \approx 62$ nΩ
@2 K, f=801.58 MHz, RRR 300

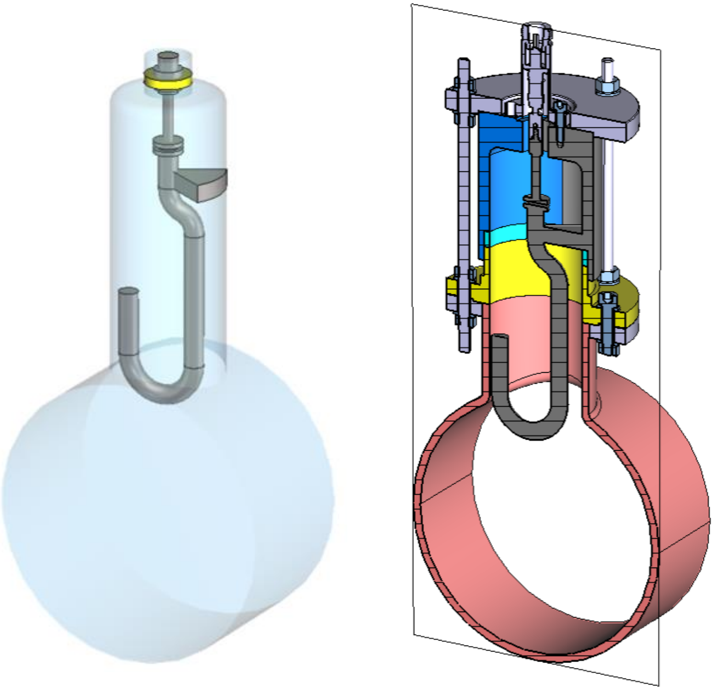


	$P_{diss\text{-}inner}$ [mW]	$P_{diss\text{-}outer}$ [mW]	T_{max} [K]
Hook (FPC side)	7.12	2.99	4.19
Hook (Tuner side)	4.69	1.97	3.89
Probe (FPC side)	8.21	2.80	6.28
Probe (Tuner side)	4.83	1.78	5.35

Inner conductor	E_{pk} [MV/m] - FM	B_{pk} [mT] - FM
Hook (FPC side)	18.38	18.54
Hook (Tuner side)	22.01	13.65
Probe (FPC side)	18.42	18.54
Probe (Tuner side)	16.30	18.98

Hook-type HOM coupler: from RF design to the 3D-printing

RF (CST) and Mechanical model



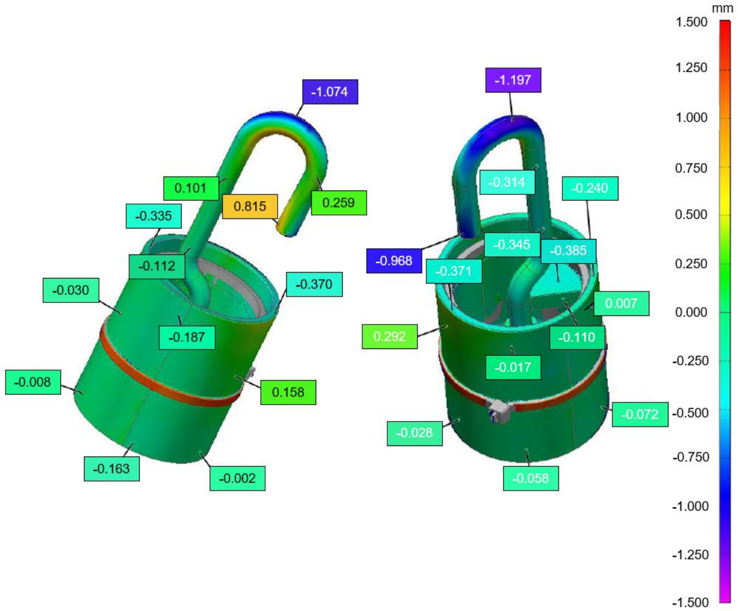
Courtesy of: Samuel Roset (IJCLab)

3D-printed prototype (Accura25 and Accura 48)

Copper-coated prototype

Courtesy of: CERN Polymerlab, Romain Gerard, and Pierre Maurin

Metrological analysis

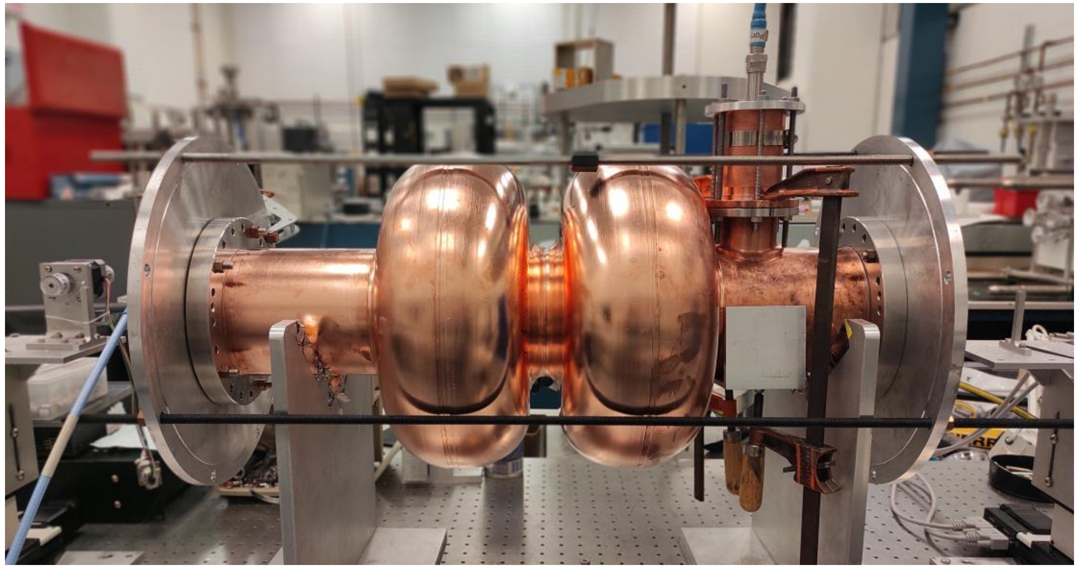


Courtesy of: Jean-Philippe Rigaud

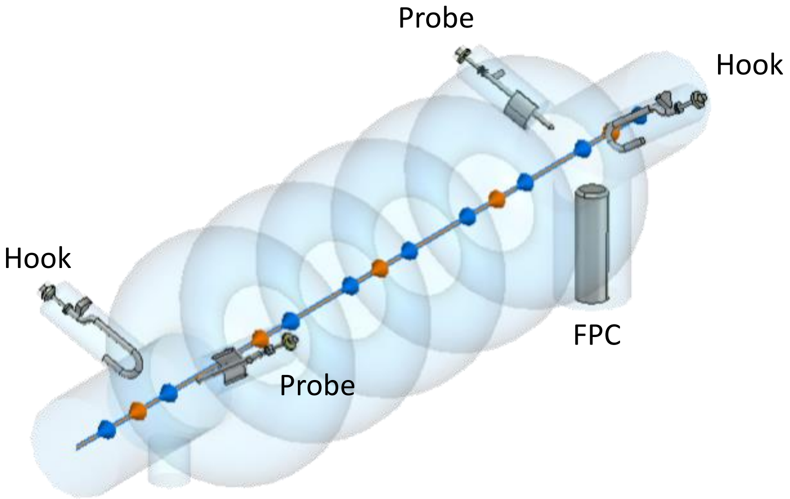
- Fruitful collaboration between IJCLab, Jefferson Lab and CERN in the framework of the PERLE project
- Mechanical design of the Hook coupler for the PERLE cavity has been made at IJCLab
- The coupler has been 3D printed in epoxy and copper coated at CERN Polimer Lab
- HOM coupler port was fabricated in Cu at Jefferson Lab, and SS flanges at IJCLab

HOM coupler: measurements

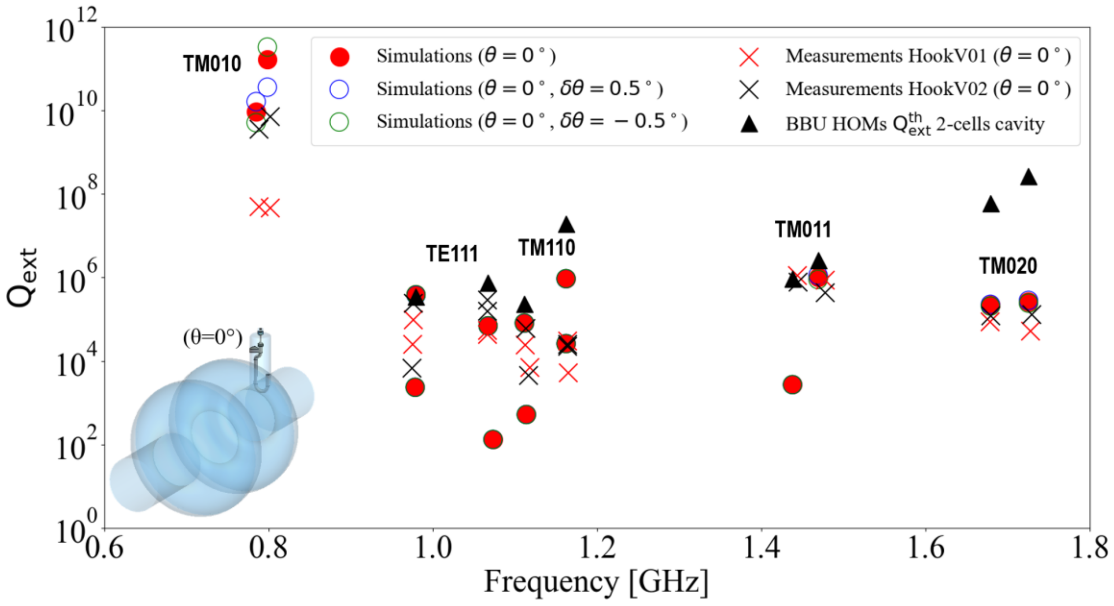
- The coupler installed at JLab on a 2-cell 801.58 MHz copper elliptical cavity to test HOM coupler performance

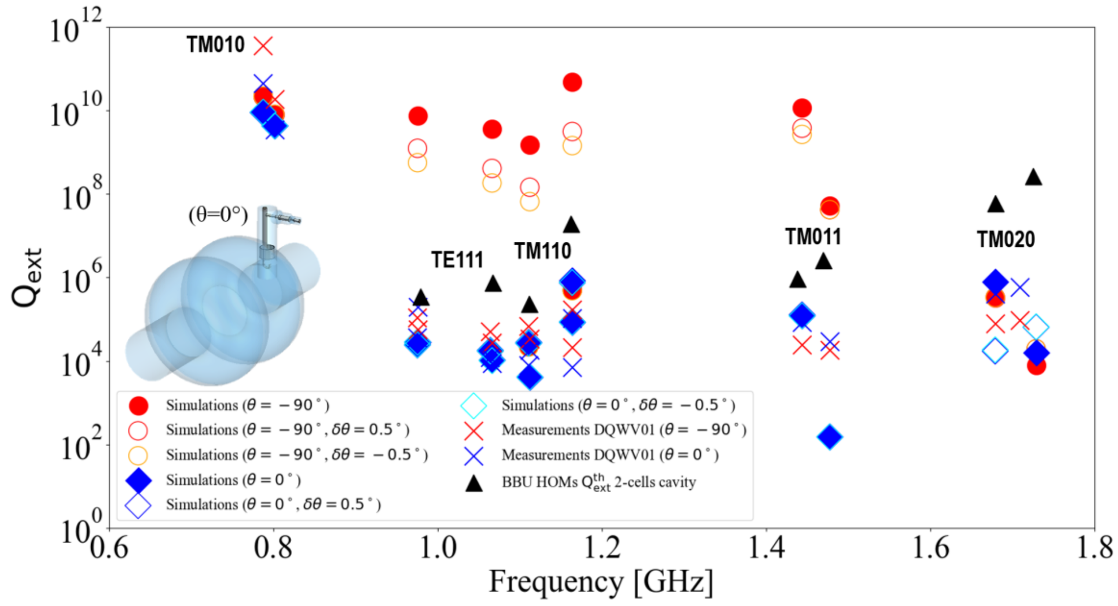


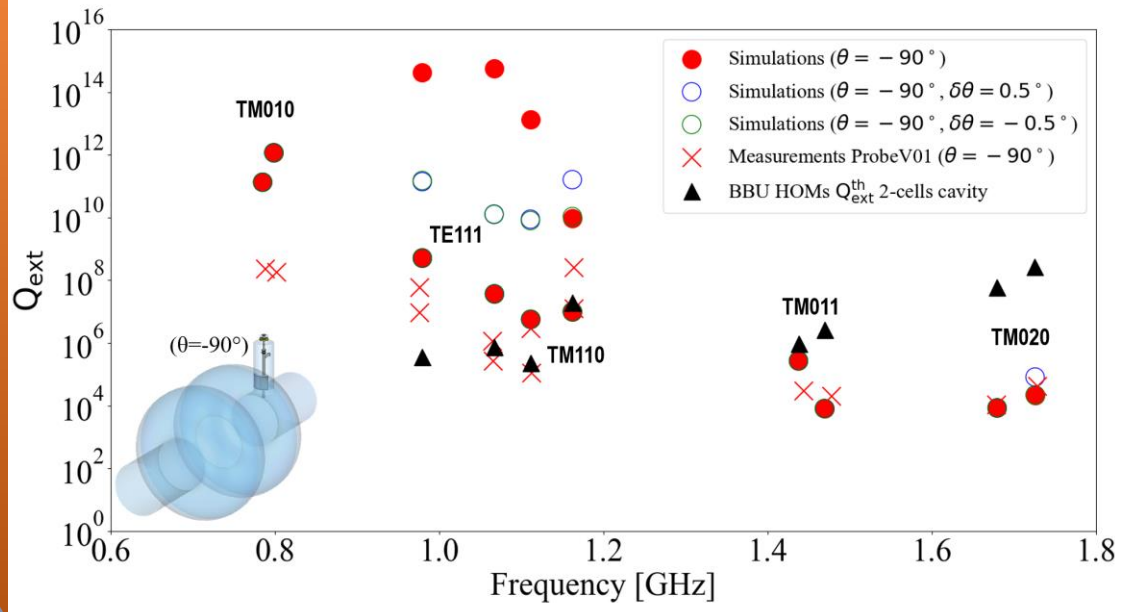
- Measurement of S12, β_1, β_2, Q_L and Q_{ext} for the HOM Hook-type, Probe-type and DQW-type coupler.
- We ultimately aim to test several combinations of HOM couplers to assess the best HOM damping scheme for the 5-cell PERLE cavity.
- Finally, we aim to produce Nb HOM couplers and install them on the Nb 5-cell PERLE cavity.



RF measurements: results







- CST results agree with measurements
- The couplers demonstrated satisfactory performance in rejecting the FM and in damping HOMs.
- Measured Q_{ext} values meet the BBU requirements
- The DQW coupler is our preferred solution for damping both monopole and dipole HOMs
- Some modes deviate from their simulated value (cavity imperfection, weak RF contact in the clamped assembly)
- Small coupler tilt can cause a change in Q_{ext} by several orders of magnitude
- Difficulty in separate polarization of dipoles in VNA

Conclusions and perspectives

Conclusions:

- Three coaxial HOM couplers were geometrically optimized to improve RF transmission and damp potentially dangerous monopole and dipole HOMs of the PERLE cavity
- The multi-pass BBU effect was studied through analytical formulation to calculate the maximum allowed Q_{ext} for each HOM and, ultimately, the current threshold in a multi-pass ERL
- 4 DQW couplers provide better damping for dipole and monopole HOMs in the 5-cell cavity. Computed impedance levels are below the analytically-computed beam-stability limits
- HOM power deposition was computed, showing that coaxial couplers have a small ratio of power extraction so that BP absorbers are needed to evacuate the power propagating out of the BPs
- RF-heating analyses were performed on the HOM couplers. The maximum field, temperature, and power dissipation were computed. Active cooling might be needed if we consider static load coming from RF cable
- HOM couplers were successfully fabricated in additive manufacturing (epoxy + copper coating) at CERN
- RF measurements of HOM couplers were performed in a 2-cell cavity at JLab, showing good agreement with simulations

Future studies:

- Test of HOM couplers on the 5-cell 801.58 MHz copper cavity under fabrication at Jefferson Lab
- Simulate beam stability thresholds through tracking codes (PLACET2, BMad, others)
- Evaluate if active cooling of the coupler antenna is required.

Acknowledgments

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- Lancaster University & Cockcroft Institute, Daresbury Laboratory: Sadiq Setiniyaz, Robert Apsimon, Peter Williams

Thank you for your attention!

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