HOM-damping studies of a 5-Cell Elliptical Superconducting Cavity for PERLE

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Outline

1. What is PERLE?
2. PERLE SRF Cavity – JLab design
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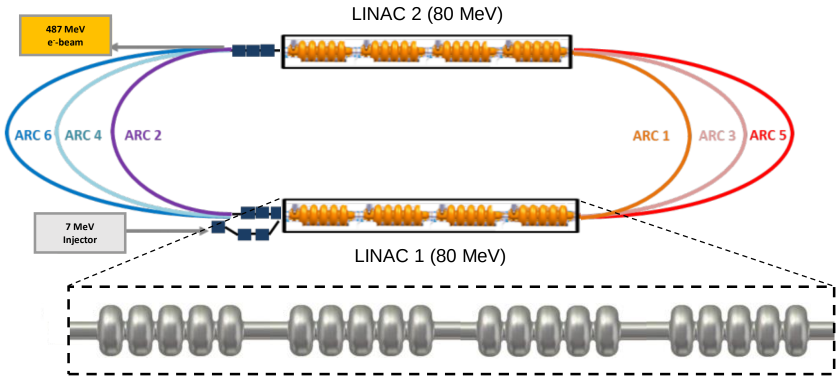
5. HOM coupler power transmission studies and coupler optimization
6. HOM-damping studies
7. Future perspectives
8. Conclusions

What is PERLE?

- **PERLE** (**P**owerful **E**nergy **R**ecovery **L**inac for **E**xperiments): multi-turn ERL based on 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 ϒεx,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)	

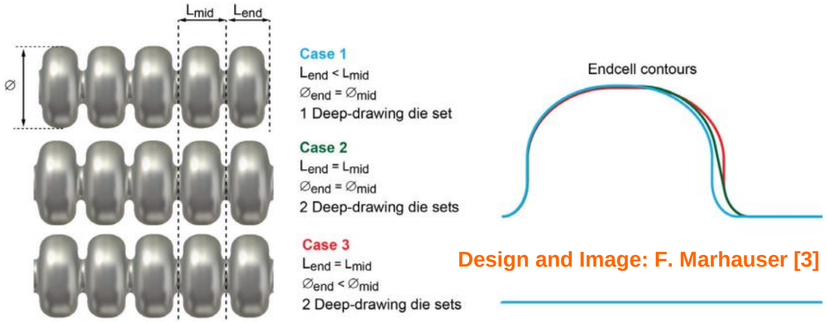
- 2 Linacs (Four 5-Cell 801.58 MHz SC cavities)
- 3 turns (160 MeV/turn): 3 passes 'up' to reach the maximum energy, 3 passes 'down' for energy recovery
- Maximum electron beam energy: 500 MeV

- **IJCLab** is today leading the PERLE project in the context of a collaboration between international partners:

PERLE SRF Cavity – JLab design

- **Objective**: design and prototyping of a full **dressed SRF cavity** required in CW operation, with adequate HOM damping.

- First 801.58 MHz 5-cell elliptical Nb cavity already fabricated at **JLab** on October 2017 (**JLab Case 1 Cavity**)

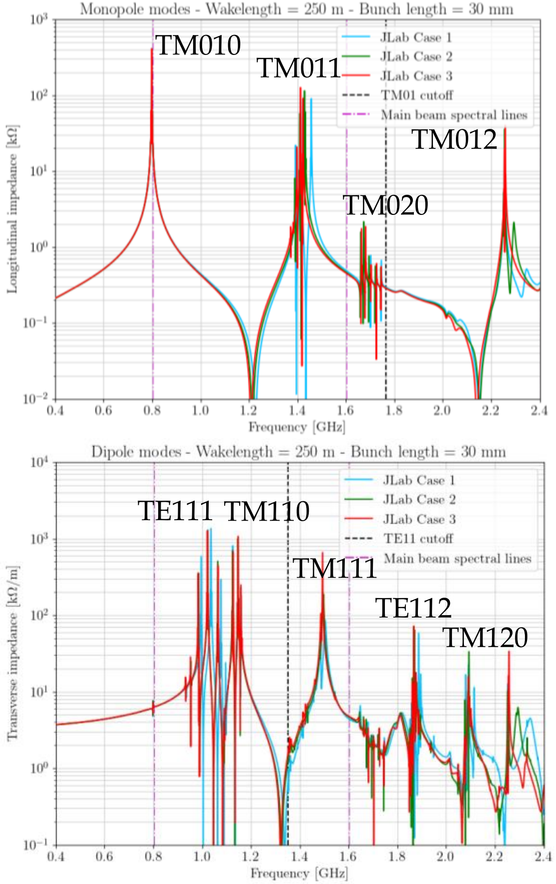


Design and Image: F. Marhauser [3]

Parameters*	JLab Case 1	JLab Case 2	JLab Case 3
Frequency [MHz]	801.58	801.58	801.58
Number of Cells	5	5	5
Material	Bulk Nb.	Bulk Nb.	Bulk Nb.
Temperature [K]	2.0	2.0	2.0
Cavity active length [mm]	917.911	935.536	935.536
Mid-cell length [mm]	187.107	187.107	187.107
End-cell length [mm]	178.295	187.107	187.107
R/Q [Ω]	524.25	520.63	522.70
(R/Q)/(cell number) [Ω]	104.85	104.13	104.54
Geometry Factor (G) [Ω]	274.505	201.490	278.112
G*(R/Q) [Ω^2]	143909.2	149901.7	145369.1
(R/Q)*G/(cell number) [Ω^2]	28781.85	29980.35	29073.83
B_{pk}/E_{acc} (mid-cell) [$mT/(MV/m)$]	4.62	4.70	4.66
E_{pk}/E_{acc} (mid-cell) [-]	2.38	2.30	2.27
Iris radius [mm]	65	65	65
Beam Pipe radius [mm]	65	65	65
Mid-cell equator diameter [mm]	328	328	328
End-cell equator diameter [mm]	328	328	325
Wall angle [degree]	0	11.95	0
Cell-to-cell coupling of mid cells [%]	2.93	2.92	2.91
$k_{\|\|}(\sigma_z = 3\text{ mm})$ [V/pC]	2.74	2.4	2.74
Cutoff TE11 [GHz]	1.35	1.35	1.35
Cutoff TM01 [GHz]	1.77	1.77	1.77

Note: $Q_{ext} \sim 10^7$ → 50 kW allows for sufficient margin during transients → detuning ~ 51.9 Hz

Impedances are for bare cavity and the peaks are not fully resolved

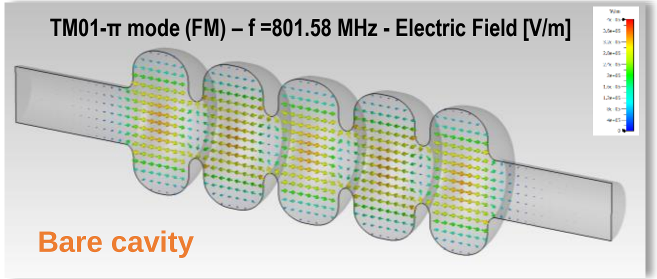


HOM numerical simulations (CST Studio Suite®)

- **HOM-damping for ERLs** is a **challenge** due to the presence of many turns.

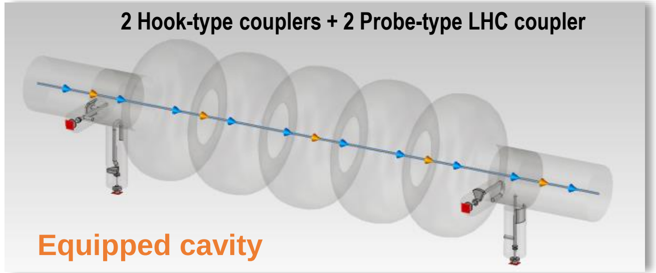
- **3D-Eigenmode simulations (bare and equipped cavity)**
  - Main RF parameters (table slide 4)
  - Identification of dangerous **HOMs**
  - **R/Q** and field distribution

All simulations were done for JLab Case1 Cavity


TM01-π mode (FM) – f =801.58 MHz - Electric Field [V/m]

Bare cavity

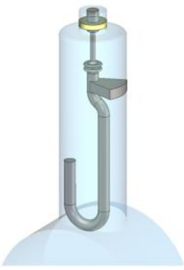
- **3D-Wakefield simulations (cavity-beam interaction)**
  - Longitudinal impedance ($\mathbf{Z_L}$ [Ω])
  - Transverse impedance ($\mathbf{Z_T}$ [Ω/m])

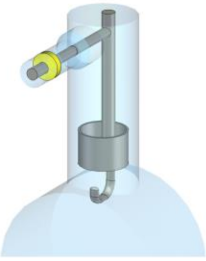

2 Hook-type couplers + 2 Probe-type LHC coupler

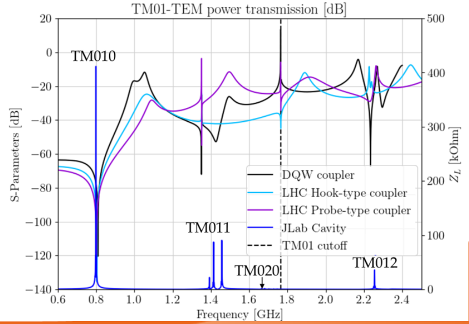
Equipped cavity

- **HOM-coupler power transmission**
  - **S-parameter** [dB] calculation
  - Coupler optimization (*recently started*)


LHC Probe-type coupler


LHC Hook-type coupler


DQW coupler



3D-Eigenmode simulations – JLab Case 1 Bare Cavity*

***3D-Eigenmode simulations on equipped cavity (cavity + HOM coupler + PC) are still in progress**

Longitudinal shunt impedance [Ω]

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

Transversal shunt impedance [Ω/m]

$$\frac{R}{Q}_{t,n} = \frac{\frac{\left|V_{\perp x,n}(0,0)\right|^2}{\omega_n U_n} + \frac{\left|V_{\perp y,n}(0,0)\right|^2}{\omega_n U_n}}{r_0}$$

Longitudinal loss factor [V/pC]

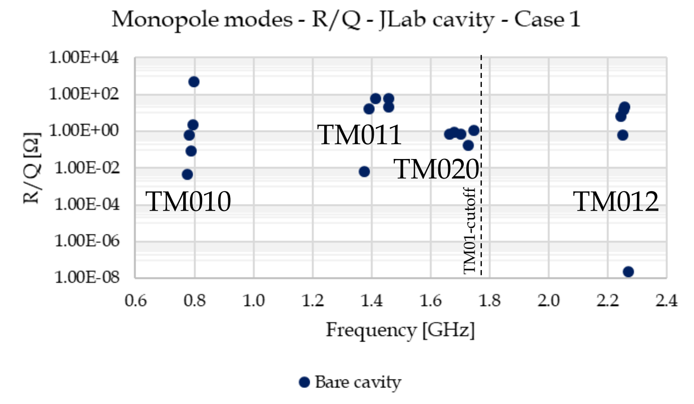
$$k_{||,n} = \frac{\omega_n}{4}\frac{R}{Q}_{||,n}$$

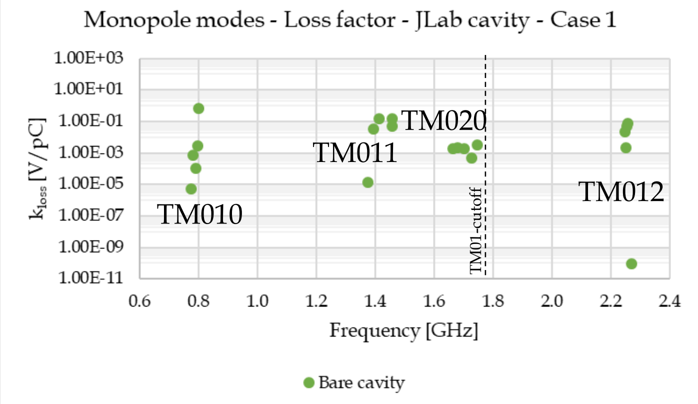
Transversal loss factor [V/(mm·pC)]

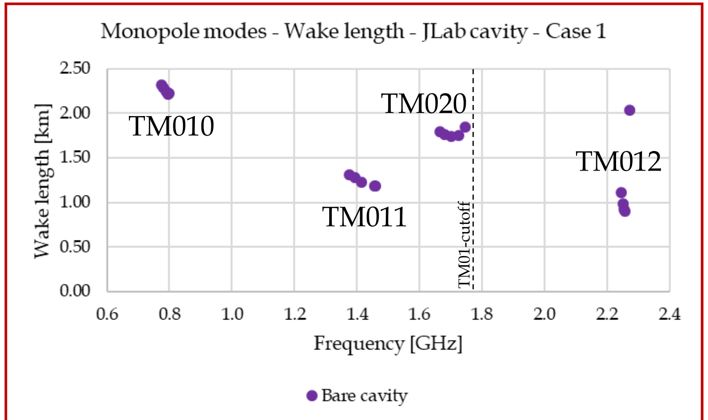
$$k_{t,n} = \frac{\frac{\omega_n^2 r_0}{c}\frac{R}{Q}_{t,n}}{r_0}$$

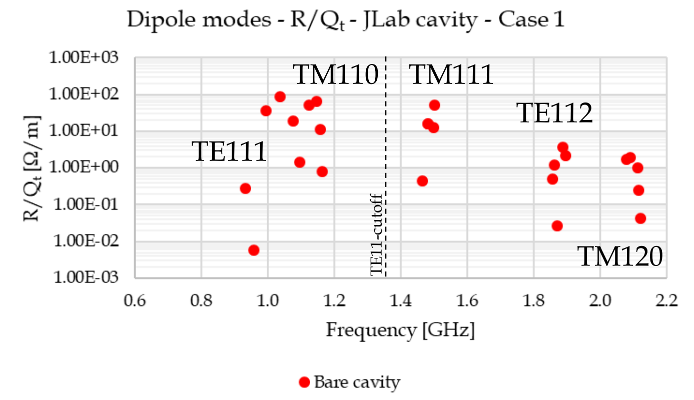
Wake length* [km]
(for σ_{Cu}=5.80E+07 $\Omega^{-1}m^{-1}$)

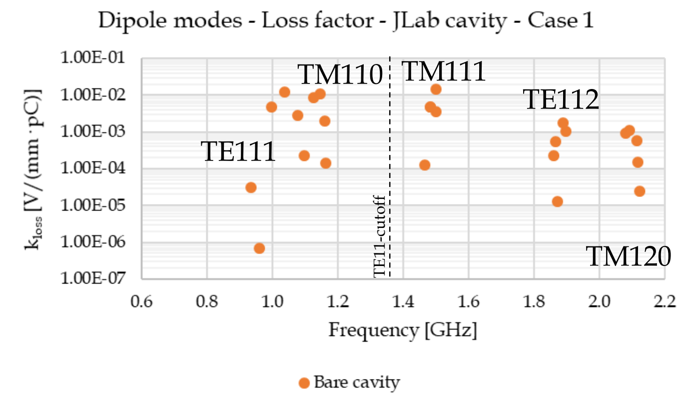
$$w_l = c\tau_n = c\frac{Q}{\omega_n}$$

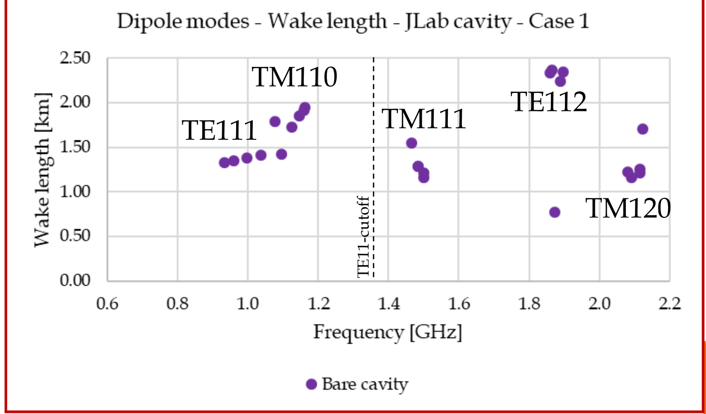

Monopole modes - R/Q - JLab cavity - Case 1


Monopole modes - Loss factor - JLab cavity - Case 1

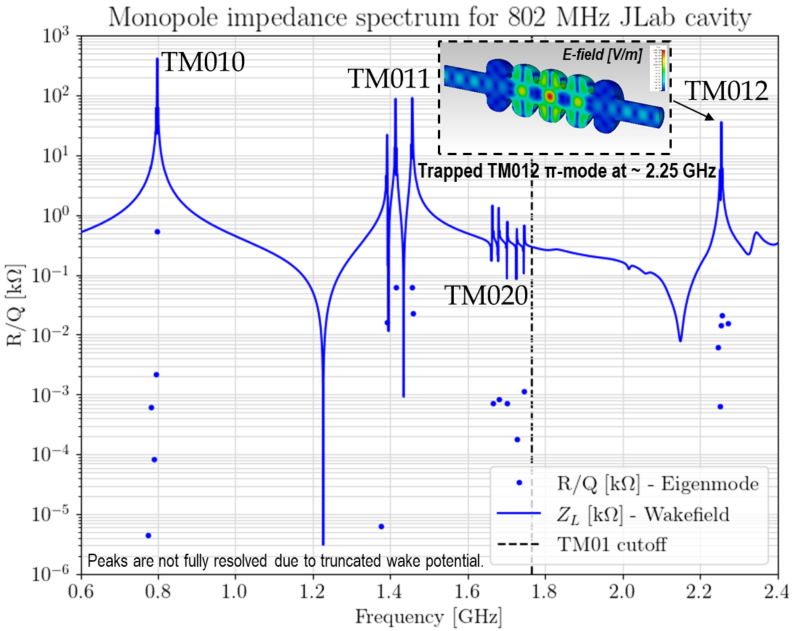

Monopole modes - Wake length - JLab cavity - Case 1

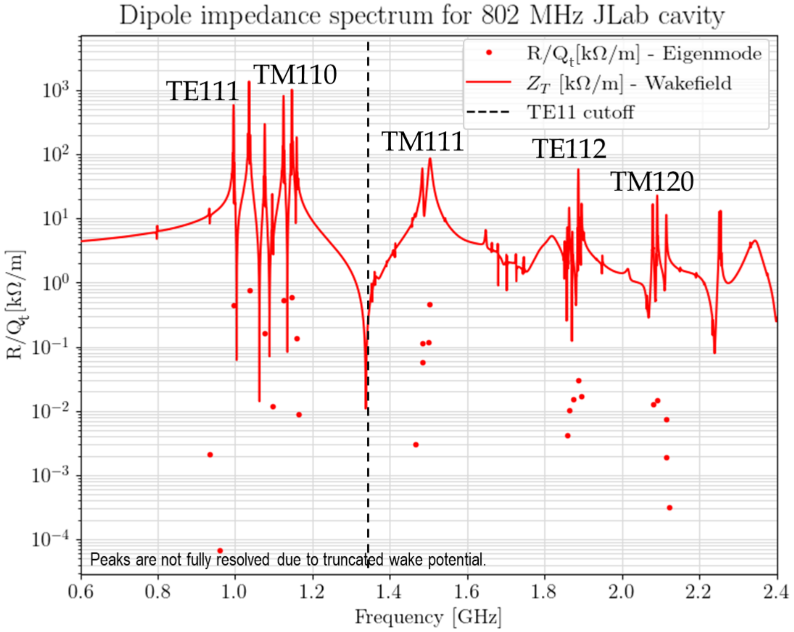

Dipole modes - R/Q$_t$ - JLab cavity - Case 1


Dipole modes - Loss factor - JLab cavity - Case 1


Dipole modes - Wake length - JLab cavity - Case 1

3D-Wakefield simulations – JLab Case 1 Bare Cavity





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

- E-field component along cavity axis
- Trapped mode can interact with the subsequent bunch
- Relative inefficient coupling of the TM012 π-mode to the beam tubes

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.

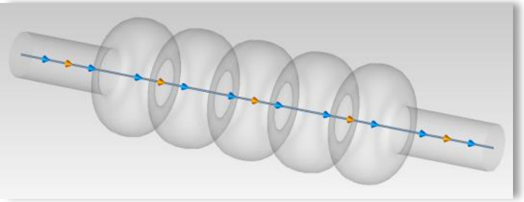
3D-Wakefield simulation:

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]

$$\boldsymbol{Z}_{\mathbf{T}}(\mathbf{r},\omega) = \frac{-j}{r_0 c}\int_{-\infty}^{\infty} \boldsymbol{w}_{\mathbf{T}}(\mathbf{r},s)\, e^{-\frac{j\omega s}{c}}\, ds$$



Wakefield simulation parameters JLab Case 1	
Beam velocity β [-]	1
RMS bunch length [mm]	30
Wake length [m]	250
Number of samples [-]	1E+06

HOM coupler power transmission studies

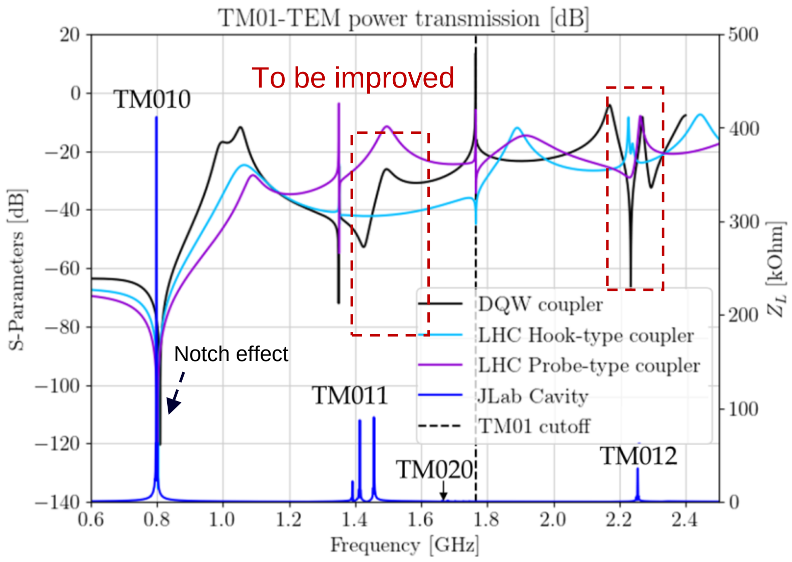
S-parameters [dB] simulation
(frequency domain solver)

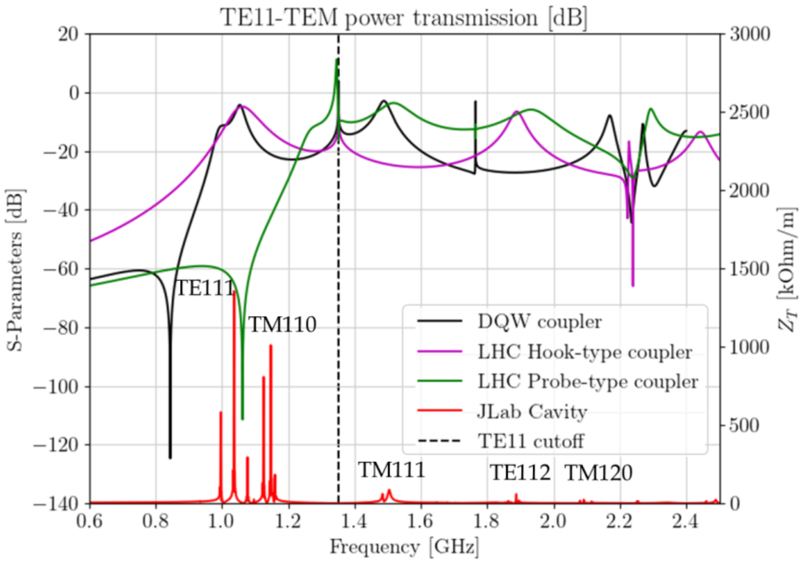
For a device with n ports

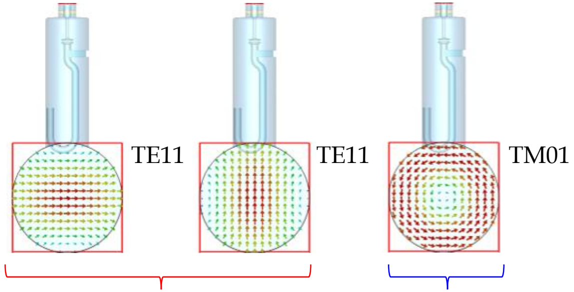
$$S = \begin{bmatrix} S_{11} & S_{12} & . & . & S_{1n} \\ S_{21} & S_{22} & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ S_{n1} & . & . & . & S_{nn} \end{bmatrix}$$

S_{ii} for reflected power

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







TE11-TEM coupling

TM01-TEM coupling

TM01-TEM transmission

- The notch effect of all couplers is tuned to 801.58 MHz for the monopole coupling.
- Couplers still need to be optimized to deliver a higher value of transmission for the TM011 and TM012 passband.

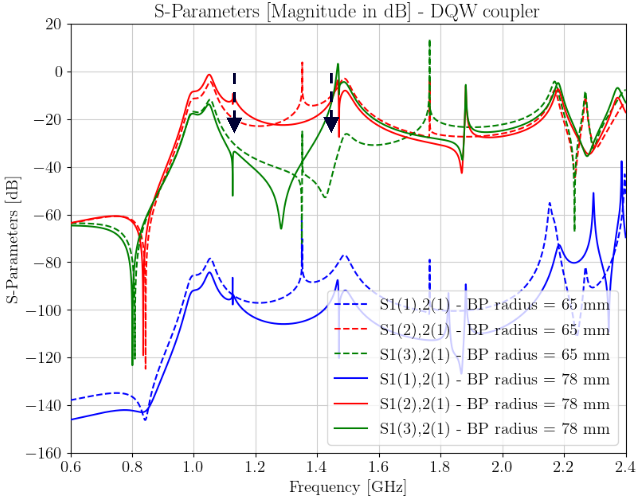
TE11-TEM transmission

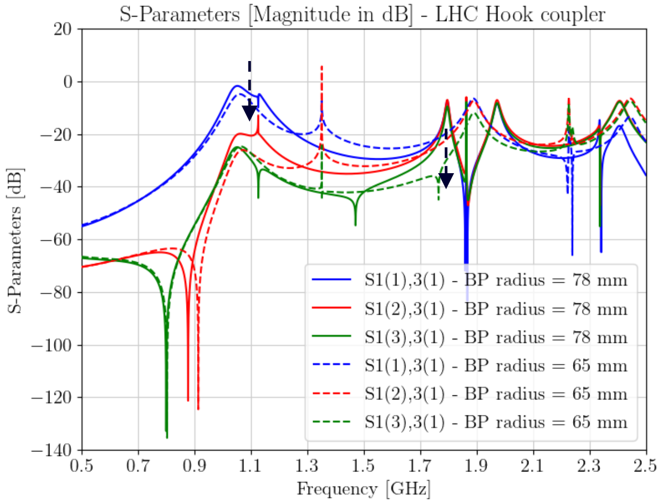
- Hook coupler gives a higher transmission than DQW coupler for the TE111 and TM110 passband.

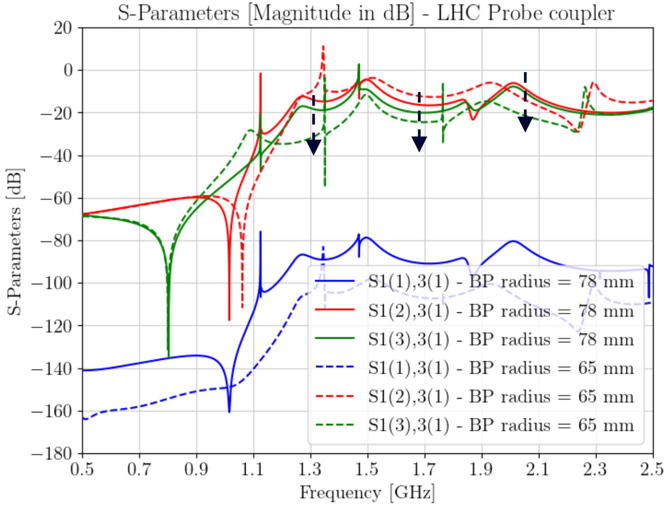
Why do we need to optimize HOM couplers?

HOM coupler models used in our simulations were initially designed for a beam tube radius of R=78 mm (801.58 MHz Rostock University cavity).

- JLab 5-cell cavity has a 65 mm beam tube radius.
- S-curves are very sensitive to geometrical changes of couplers.
- Installation of current couplers in R=65 mm tubes: drop in performance in certain frequency ranges where HOMs need to be damped.





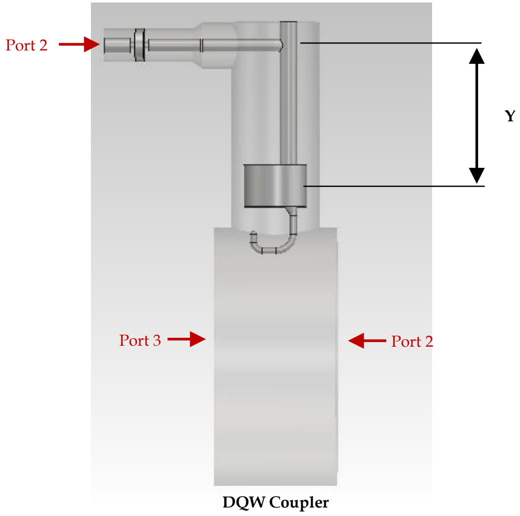


Optimization is needed: **DQW coupler** can assure a high transmission for both first higher order monopole and dipole passband.

HOM coupler optimization – Methods

CST Studio Suite

- Solver: Frequency domain solver
- Optimizer algorithm: Trust region framework, CMA evolution strategy…



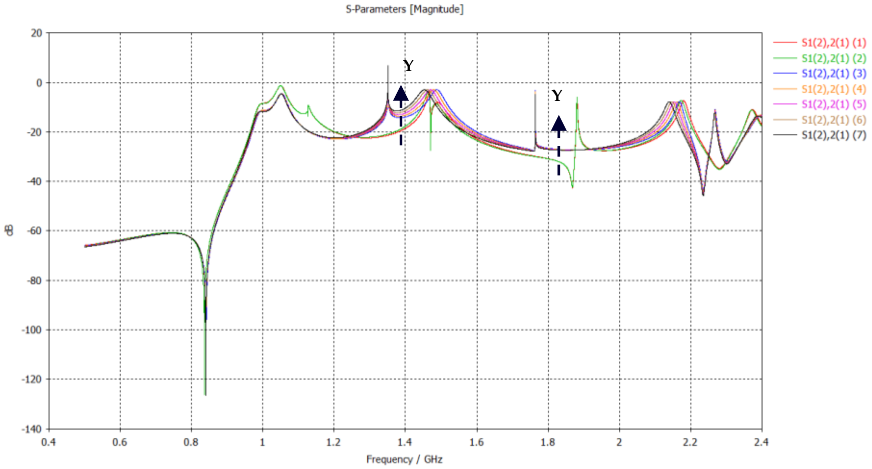
DQW Coupler

STEP 1: parameter sweep analysis (one-parameter-at-a-time)

- Build a parametric geometry (max 40 parameters) of the HOM coupler
- Each parameter corresponds to a specific part of the HOM coupler equivalent circuit
- See the influence of each geometrical parameters on S-curves
- Find out which parameters play a more important role in changing S-curves

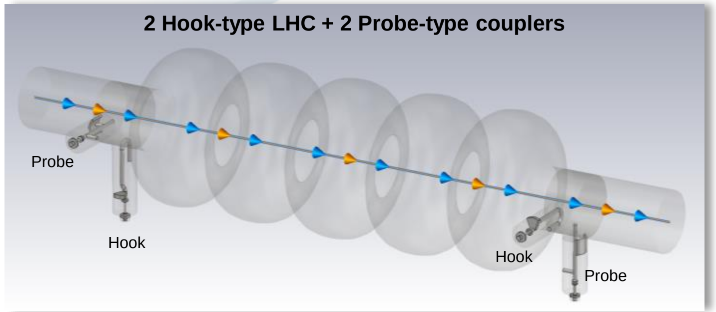
STEP 2: CST optimizer to fine-tune

- Definition of the objective functions (minimization of the highest impedances)
- Optimization of multiple parameters at the same time (max 5 parameters).

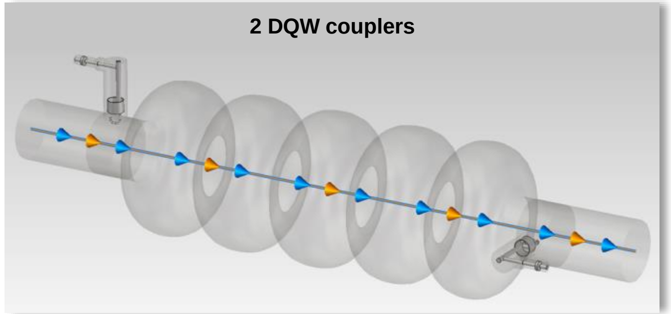


HOM-damping schemes

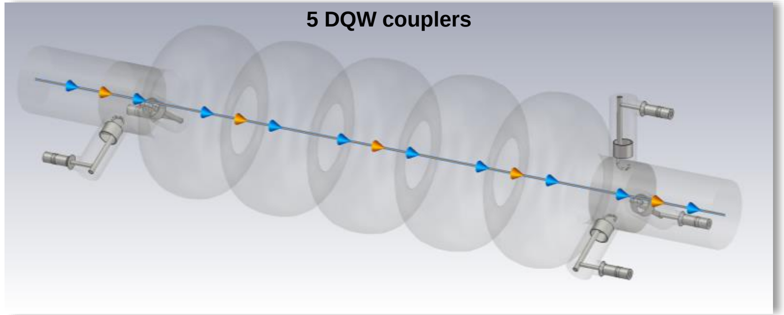
5-cell cavity + HOM couplers



2 Hook-type LHC + 2 Probe-type couplers

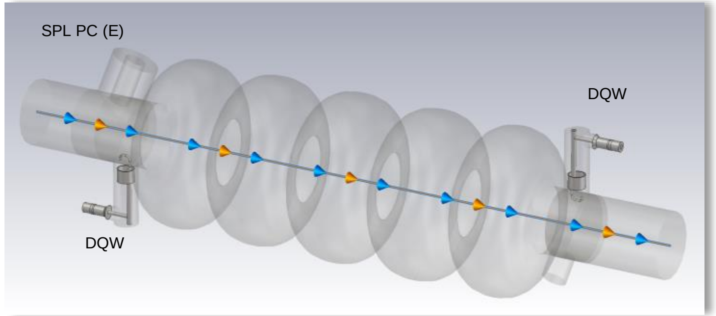


2 DQW couplers



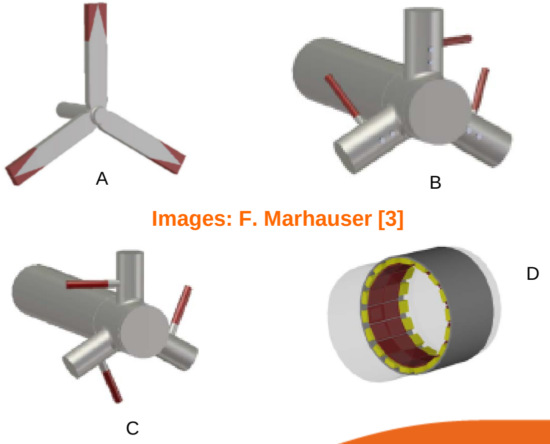
5 DQW couplers

5-cell cavity + HOM couplers + SPL Power Coupler



Other suitable HOM-damping schemes :

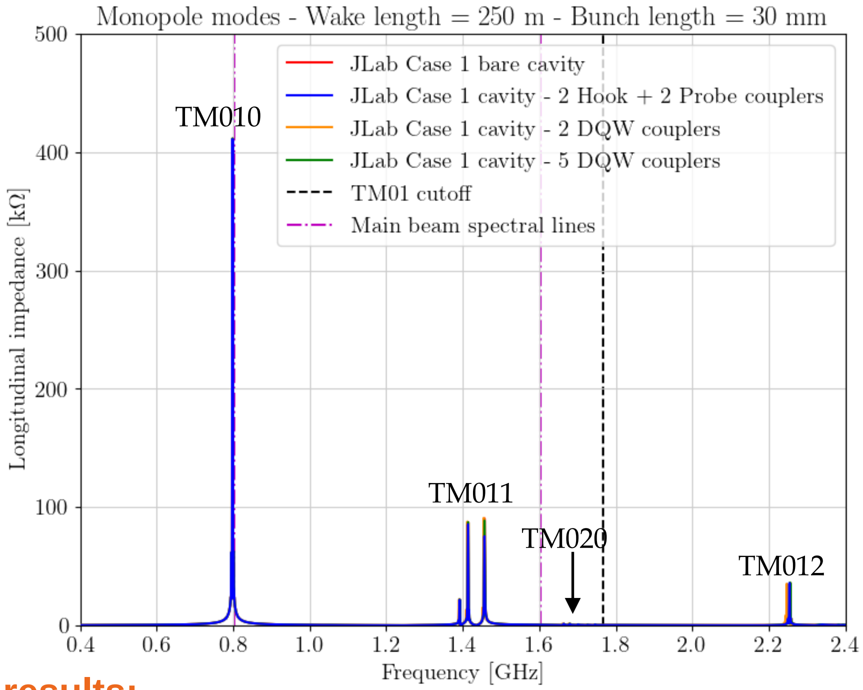
- Rectangular waveguide dampers (A)
- JLab-Type coaxial couplers (B)
- TESLA-Type coaxial couplers (C)
- Add absorbers in cavity-interconnecting beam tubes (D)
- Coupling through Fundamental Power Coupler (E)

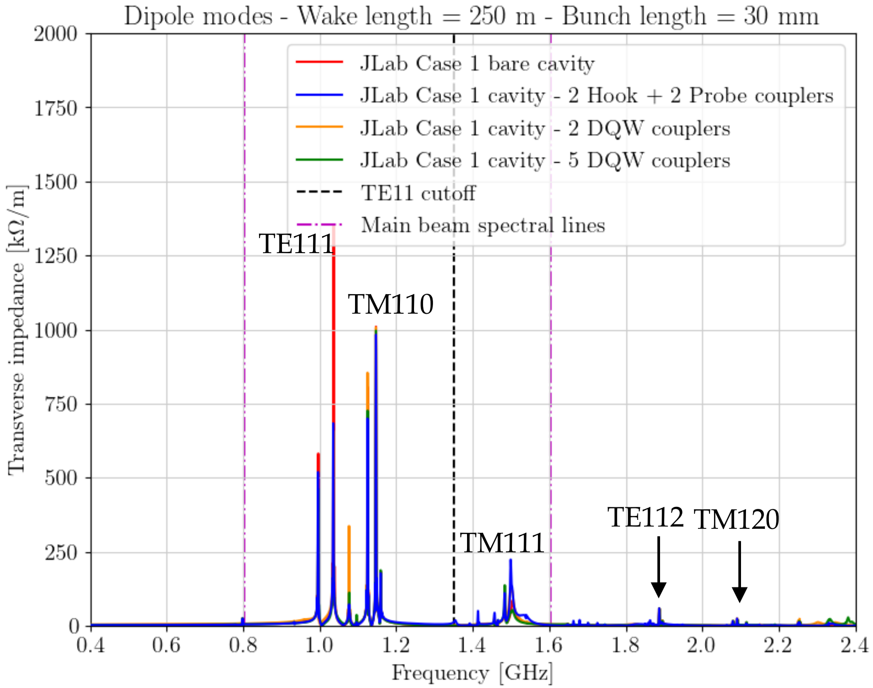


Images: F. Marhauser [3]

HOM-damping studies

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





Preliminary results:

- 2 Hook + 2 Probe couplers configuration seems to provide a better damping than the DQW couplers configurations. However, DQW couplers have still to be optimized!
- Peaks are not fully resolved. **Extrapolated impedance spectra** need to be calculated (JLab's method) [9]
- Trapped TM012 mode was not damped in the investigated configurations (end-cells modification is needed)

Future perspectives – HOM Power

Average HOM power deposited by the beam in the cavity

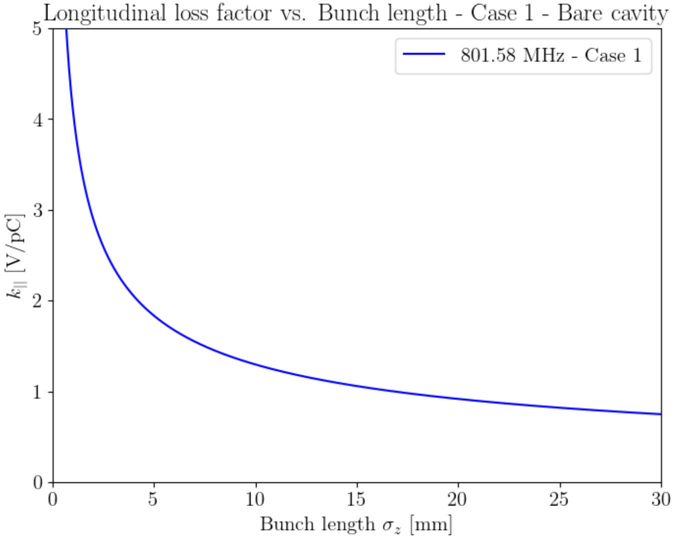
$$P_{HOM} = k_{||,HOM} Q_b I_0$$

If the main spectral line of the beam falls on the HOM resonance of the cavity, the voltage increases as well as the HOM power

$$\boxed{P_{HOM} = \frac{R}{Q} Q_L I_0^2}$$

Objective 1: estimate the HOM power once we will have the bunch spectrum of the beam available.

Objective 2: doing a thermal study on HOM couplers



RF and beam parameters	PERLE	PERLE @ Orsay
Q_b	320 pC	500 pC
I_0	15 mA	20 mA
σ_z	3 mm	3 mm
$k_{\|\|}$	2.742 V/pC	2.742 V/pC
$k_{\|\|,0}$	0.657 V/pC	0.656 V/pC
P_{HOM} (1 pass)	**10.009 W**	**20.862 W**

Future perspective – Experimental activities

Experimental activities:

- Cavity end-cell modifications (improve the damping of TM011 and TM012 mode)
  - Do we plan to do perform the modifications at JLab or at CERN, where and when (**Q1** 2022)?
  - Measurements on the cavity

- Tube modification to install HOM couplers

- Realization of the HOM couplers and installation on the cavity

- Integration of the PERLE cavity in the SPL cryomodule

- Thermal treatments (Nitrogen doping) on the cavity

- Integration of the SPL Power Coupler

- Test of the full dressed cavity on the vertical cryostat

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 two DQW coupler configurations. However, couplers need still to be optimized.

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)

- Planning of the experimental activities (CERN and JLab)

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Thank you for your attention!

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Backup slides

HOM numerical simulations: methods

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

Helmholtz equations

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

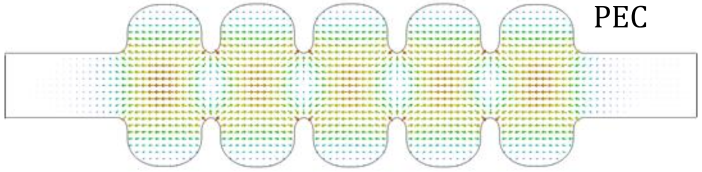
$$\nabla^2\underline{\mathbf{H}} + \omega^2\mu\varepsilon\underline{\mathbf{H}} = 0$$

Boundary conditions

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

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

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.

Eigenmode simulations

Longitudinal shunt impedance [Ω]

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

Transverse shunt impedance [Ω/m]

$$\frac{R}{Q}_{t,n} = \frac{\dfrac{\left|V_{\perp x,n}(0,0)\right|^2}{\omega_n U_n} + \dfrac{\left|V_{\perp y,n}(0,0)\right|^2}{\omega_n U_n}}{r_0}$$

Wakefield simulations

Longitudinal impedance [Ω]

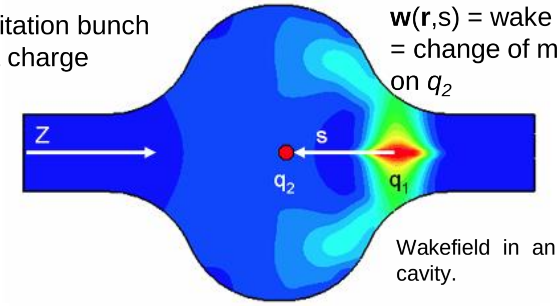
$$Z_{\mathrm{L}}(\mathbf{r},\omega) = \frac{1}{c}\int_{-\infty}^{\infty} w_{\mathrm{L}}(\mathbf{r},s)\, e^{-\frac{j\omega s}{c}} ds$$

Transverse impedance [Ω/m]

$$\boldsymbol{Z}_{\mathbf{T}}(\mathbf{r},\omega) = \frac{-j}{r_0 c}\int_{-\infty}^{\infty} \boldsymbol{w}_{\mathbf{T}}(\mathbf{r},s)\, e^{-\frac{j\omega s}{c}} ds$$

q_1 = excitation bunch
q_2 = test charge

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



Wakefield in an elliptical cavity.

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

Calculation of the HOM power (1 pass)

bunch charge

- $P_{HOM} = k_{||,HOM} Q_b I_0$ HOM power (1 pass)

average beam current

Total longitudinal loss (CST wakefield)

- $k_{||,HOM} = k_{||} - k_{||,0}$ Longitudinal loss factor

Loss factor of FM (Fundamental Mode)

Longitudinal impedance (CST wakefield)

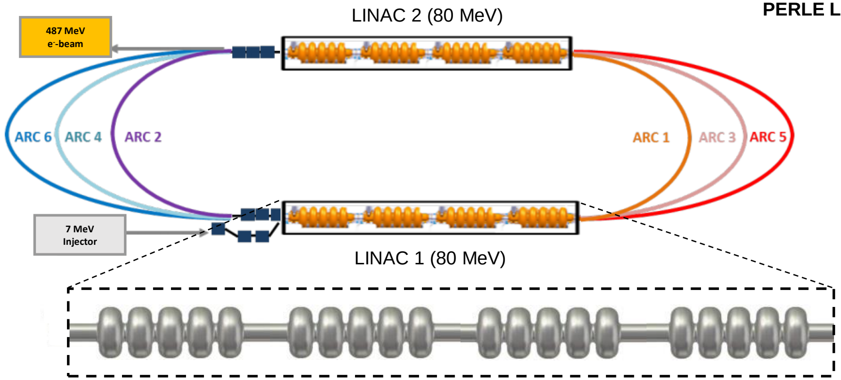
- $k_{||}(\sigma_z) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} Z_{||}(\omega) e^{-\left(\omega \sigma_z / c\right)^2} d\omega$

- $k_{||,0} = \frac{\omega_0}{4} \frac{R}{Q_{||,0}} e^{-\left(\omega_0 \sigma_z / c\right)^2}$

Geometric shunt impedance (Fundamental Mode)

RF and beam parameters	**PERLE**	**PERLE @ Orsay**
Q_b	320 pC	500 pC
I_0	15 mA	20 mA
σ_z	3 mm	3 mm
$k_{\|\|}$	2.742 V/pC	2.742 V/pC
$k_{\|\|,0}$	0.657 V/pC	0.656 V/pC
P_{HOM} (1 beam)	**10.009 W**	**20.862 W**

PERLE LAYOUT



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]