

RF Component Design Issues

USPAS
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Introduction

- Computer codes are invaluable as an analysis tool for calculating *E&M* fields of RF components that have complex geometries whose fields are difficult or impossible to solve analytically
- Helpful in understanding the component and its effects on beams
- Components in an accelerator interact with and affect the performance of charged particle beams.
- Active components provide *E&M* fields to keep the beam in the design orbit. These include RF cavities, kickers, injection and extraction kickers, ...
- Passive components may introduce impedance to the beam and cause beam instability. These include vacuum chambers, bellows, joints, BPMs, target boxes, pumping slots, ...

Voltage / Shunt Impedance / Quality Factor

- Voltage is the integration of the longitudinal electric field along the axis. The finite time of travel of the beam through the cavity is accounted for by the exponential term, i.e., the “transit time factor”.

$$V_z = \int E_z(x, y, z) e^{j\omega z/v} dz$$

Accounts for transit time factor due to finite speed of particle

- Shunt impedance, R_s is an important measure of the efficiency of the accelerator in transferring energy to the particle beam

$$R_s = \frac{\left| \int E_z(x, y, z) e^{j\omega z/v} dz \right|^2}{P_L}$$

- Q is a measure of the rate at which rf energy is removed from the cavity. It is used to determine the cavity bandwidth and modal interaction in the cavity.

$$Q = \frac{\omega U}{P_L}$$

Both R_s and Q vary depending upon the material properties of the cavity

Material Independent Parameters: R/Q and G

- R/Q is a parameter that eliminates the dependence on the precise material properties of the cavity. It is purely geometry dependent.
- G is used to compare various cavity shapes regardless of their size and material construction.

$$\frac{R}{Q} = \frac{\left| \int E_z(x, y, z) e^{j\omega z / v} dz \right|^2}{2\omega U}$$

$$G = \frac{\omega \mu \int_V |H|^2 dV}{\int_S |H|^2 dS} = Q_0 * R_s$$

These parameters allow the comparison of given accelerator cavity designs based purely on the merits of their geometries, not on the details of their construction

Loss Factor

- The loss factor quantifies the loss of beam energy as it passes through a structure.

$$\begin{aligned} V_\lambda &\sim \text{rf voltage of mode } \lambda \text{ that beam sees} \\ U_\lambda &\sim \text{EM storage energy of mode } \lambda \\ Q_\lambda &\sim \text{quality factor of mode } \lambda \\ P_\lambda &\sim \text{rf power loss on cavity wall} \end{aligned}$$

Wake potential induced by a point charge is given by,

$$W_{\parallel}^{\delta}(s) = [e] \sum_{\lambda=0}^{\infty} 2k_{\lambda} \cos\left(\frac{\omega_{\lambda}}{c}s\right),$$

where k_{λ} is the so called loss factor for mode λ , and defined as:

$$k_{\lambda} = \frac{V_{\lambda}^2}{4 U_{\lambda}}, \quad V_{\lambda} = \int_0^l E_{\lambda,z}(\vec{r}, z) e^{j\frac{\omega_{\lambda}}{\beta c}z} dz.$$

The loss factor is related to shunt impedance of an rf cavity by

$$k_{\lambda} = \frac{\omega_{\lambda}}{4} \left(\frac{R_{\lambda}}{Q_{\lambda}} \right), \quad R_{\lambda} = \frac{V_{\lambda}^2}{P_{\lambda}}, \quad Q_{\lambda} = \omega_{\lambda} \frac{U_{\lambda}}{P_{\lambda}}$$

Quality Factor

- Unloaded Q, Q_u , is a measure of the ohmic losses in the rf cavity walls
- External Q, Q_{ext} , is a measure of 'losses' due to coupling of the cavity fields to the outside. Coupling may be to input coupler(s), probes, and/or dampers.
- Loaded Q, Q_L , is a measure of the totality of losses due to the cavity assembly interaction, i.e., due to Q_u and Q_{ext} .
$$\frac{1}{Q_L} = \frac{1}{Q_u} + \frac{1}{Q_{ext}}$$
- Q_L determines the overall cavity bandwidth and is important when considering microphonics and Lorentz force detuning.
- Q_L is also useful in determining stability characteristics for modes that interact strongly with the beam.
- Typically, Q_{ext} is adjusted in order to ensure beam stability. This is especially important for high current machines and superconducting cavities.

Q_{ext} : Energy Decay

Q_{ext} can be measured if the decay time constant is known

$$P_{\text{tot}} = P_c + P_e$$

Total power loss
in cavity assembly

$$Q_L = \frac{\omega U}{P_{\text{tot}}}$$

Definition of
loaded Q

Rate of change of
the energy in the
cavity equals the
total power loss

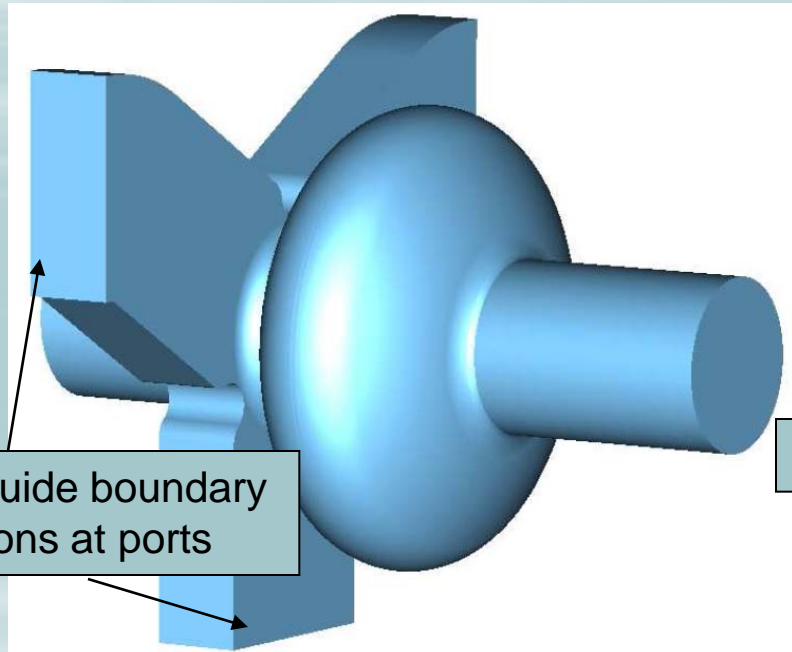
$$\frac{dU}{dt} = \frac{\omega U}{Q_L}$$

$$U = C e^{-\frac{\omega t}{Q_L}}$$

$$\tau = \frac{Q_L}{\omega} \approx \frac{Q_{\text{ext}}}{\omega}$$

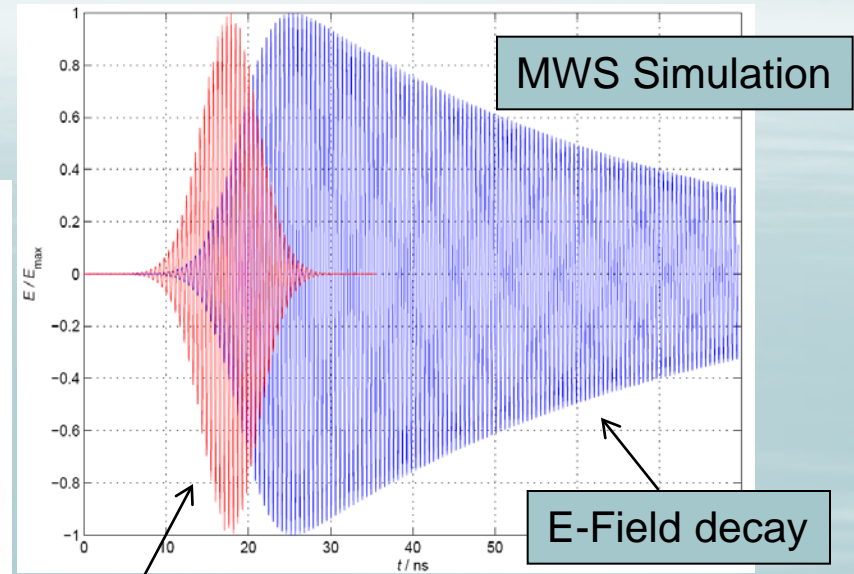
Q_{ext} can be
calculated from the
decay time constant

Q_{ext} Validations with JLAB Cavity



Waveguide boundary conditions at ports

Excite cavity from one RF (HOM) port



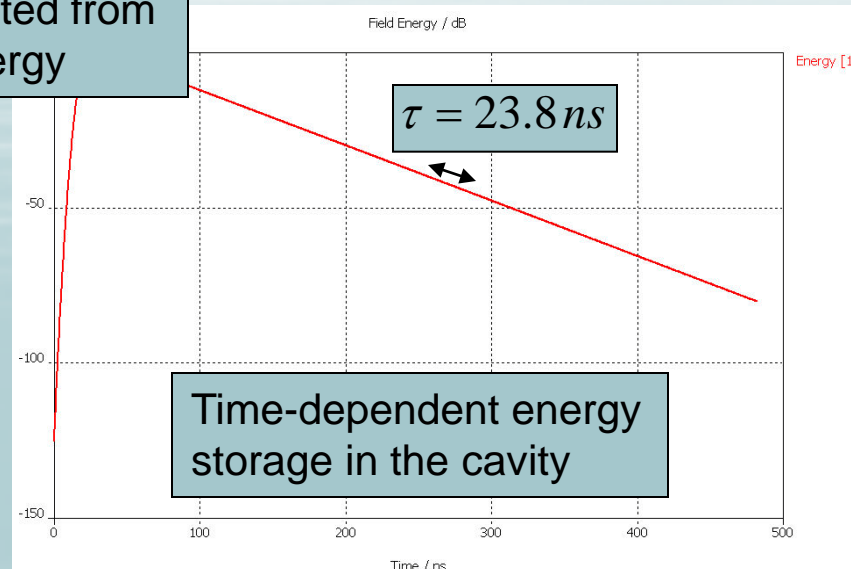
Excitation pulse

E-Field decay

Observed field (energy) decay as a function of time inside the cavity

Q_{ext} Validations with JLAB Cavity

External Q is calculated from decay time of the energy



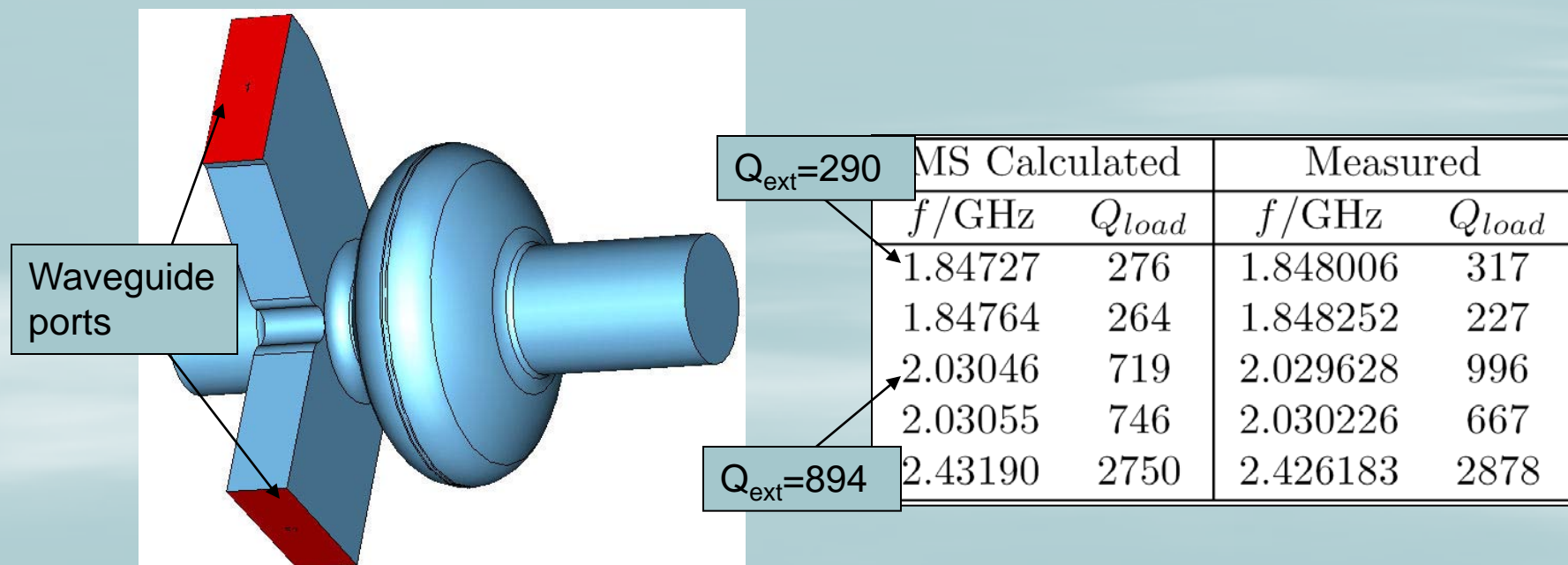
$$Q_{ext} = \omega\tau = 276$$

Simulated and measured Q_{ext} results in good agreement

MS Calculated		Measured	
f/GHz	Q_{load}	f/GHz	Q_{load}
1.84727	276	1.848006	317
1.84764	264	1.848252	227
2.03046	719	2.029628	996
2.03055	746	2.030226	667
2.43190	2750	2.426183	2878

Q_{ext} MWS Eigenmode Calculation

- Calculating Q_{ext} from the energy decay is a tedious process that must be performed for each mode.
- MWS has an automatic calculation for Q_{ext} in the eigenmode solver.
- MWS solves for all calculated modes in a single run



Q_{ext} : Balleyguier's Method

- Balleyguier's method requires two simulations runs to calculate many modes.
- Useful for any generic eigenmode solver including MWS, Mafia, and HFSS.
- Valid for a single mode coupled out of the cavity

Power traveling
out of the cavity

$$P = \frac{1}{2\eta} \int_S |E|^2 dS = \frac{\eta}{2} \int_S |H|^2 dS$$

Energy storage
in the cavity

$$U = \frac{\epsilon}{2} \int_V |E|^2 dV = \frac{\mu}{2} \int_V |H|^2 dV$$

S is along a cross-
section of the coupling
transmission line

V is the volume
within the cavity

$$Q_{ext} = \frac{\omega U}{P}$$

Determination of P requires
port absorbing boundary and
possible mode excitation

Q_{ext} : Balleyguier's Method

Add (subtract) an equal amplitude incoming electric field to the outgoing field to create a standing wave

Choose c.s. at E-field maximum (magnetic wall)

Choose c.s. at H-field maximum (electric wall)

$$Q_1 = \frac{\omega \int_V |E_1|^2 dV}{c \int_S |E_1|^2 dS} = \frac{|1 + e^{i\theta}|^2}{4} Q_{\text{ext}}$$

$$Q_2 = \frac{\omega \int_V |H_2|^2 dV}{c \int_S |H_2|^2 dS} = \frac{|1 - e^{i\theta}|^2}{4} Q_{\text{ext}}$$

$$Q_1 + Q_2 = \frac{|1 + e^{i\theta}|^2 + |1 - e^{i\theta}|^2}{4} Q_{\text{ext}} = Q_{\text{ext}}$$

Method transforms a traveling wave problem to a standing wave.

All solutions can be calculated with two runs of the eigenmode solver

Q_{ext} can be calculated by simply summing the two results

Example Coaxial Damper

