Impedance Verification for QMiR Cavity and ILC

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ILC WP3 - Specification Discussion

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Deflecting cavity for ILC

Outline:

- *General Requirements for the ILC deflecting cavities*
- *HOM impedance limitation due to resonance excitation*
  - Transverse effects
- *Single-bunch effects*
- *Required RF power*
- *Requirements for ILC*
- *QMIR*
- *Conclusions*

Requirements for the ILC deflecting cavities*

Table 5-1: New beam parameters optimized for ILC250GeV.

			TDR		New
Center-of-mass energy	E_{CM}	GeV	250	500	250
Bunch population	N	e10	2	2	2
Bunch separation		ns	554	554	554
Beam current		mA	5.78	5.78	5.78
Number of bunches per pulse	Nb		1312	1312	1312
Collision frequency		Hz	5	5	5
Electron linac rep rate		Hz	10	5	5
Beam power (2 beams)	P_B	MW	5.26	10.5	5.26
r.m.s. bunch length at IP	σ_z	mm	0.3	0.3	0.3
relative energy spread at IP (e−)	σ_E/E	%	0.188	0.124	0.188
relative energy spread at IP (e+)	σ_E/E	%	0.15	0.07	0.15
Normalized horizontal emittance at IP	ε_{nx}	µm	10	10	5
Normalized vertical emittance at IP	ε_{ny}	nm	35	35	35

- Bunch population *N =2e10*
- Number of bunches/pulse n_b=1312
- Bunch separation Δt_b= 554 nsec.
- Colliding rate f_{rep}=5 Hz
- Bunch length σ_z = 0.3 mm

* The International Linear Collider, Machine Staging Report 2017 .

Requirements for the ILC deflecting cavities*

Frequency		3.9 GHz	1.3 GHz	
# of cell		9 cell	3 cell	9 cell
Total length (pi/2 mode)		0.346 m	0.346 m	1.038 m
Total kick voltage	*Present location*	0.615 MV	1.845 MV	
	Alternative (s=77m)	0.878 MV	2.633 MV	
Cavity gradient	*Present location*	8.14 MV/m	24.4 MV/m	8.14 MV/m
	Alternative (s=77m)	11.6 MV/m	34.9 MV/m	11.6 MV/m
Relative RF phase jitter		0.069 deg rms. (49 fs rms.)	0.023 deg rms. (49 fs rms.)	

	Total kick voltage × RF frequency
Present location	2.399 MV ×GHz
Alternative	3.424 MV ×GHz

***Toshiyuki OKUGI, KEK (*11/20/2020, ITD WG2 SCRF, BDS joint subgroup meeting*)**

HOM impedance limitation due to resonance excitation

Transverse effects

The crab cavity HOM impedance should be small enough to avoid single bunch effects such as

1. Distortion of the crabbing voltage along the bunch
2. Emittance dilution

1. To avoid distortion of the crabbing voltage, horizontal kick U_{kick} caused by HOM should be much smaller than the crabbing voltage U_0. In the most pessimistic case of resonance

$$U_{kick} \ll U_0 \, \sigma_z \omega_{RF}/c, \qquad (1)$$

and

$$r_\perp \ll \frac{U_0 \, \sigma_z \omega_{RF}/c}{k_0 x_0 I_p}. \qquad (2)$$

Here ω_{RF} is the RF frequency.

HOM impedance limitation due to resonance excitation

2. To avoid emittance dilution, the transverse kick spread along the bunch caused by an HOM should be much smaller than the transverse momentum spread $\sigma_{p_\perp}$, or

$$U_{kick} \ll \frac{\sigma_{p_\perp} c}{e}, \qquad (3)$$

here

$$\frac{\sigma_{p_\perp} c}{e} = \frac{\Delta p_{||} c}{e}\sqrt{\frac{\varepsilon}{\gamma\beta}} = U\sqrt{\frac{\varepsilon}{\gamma\beta}}, \qquad (4)$$

Where U is the beam energy, ε is the normalized transverse emittance, γ is the relativistic factor and β is the beta-function corresponding to the cavity position. Therefore, for both horizontal and vertical transverse shunt impedance one needs

$$r_\perp \ll \frac{U}{k_0 x_0 I_p}\sqrt{\frac{\varepsilon}{\gamma\beta}}. \qquad (5)$$

Here $r_\perp$ is the horizontal or vertical transverse shunt impedance, x_0 is the horizontal or vertical transverse offset, and ε is the horizontal or vertical transverse normalized emittance.

Single-bunch effects

If the bunch has very high population, the kick caused by the bunch transverse *horizontal* wake potential may alter the crabbing kick voltage. This gives us limitation for the transverse kick-factor:

$$k_{\perp} \ll \frac{U_0}{q x_0 \sigma_z \omega_{RF}/c}, \qquad (6)$$

where q is the bunch charge and x_0 is the beam *horizontal* offset. The transverse *vertical* wake potential should not increase the bunch emittance:

$$k_{\perp} \ll \frac{U}{q x_0} \sqrt{\frac{\varepsilon}{\gamma \beta}}. \qquad (7)$$

Here x_0 is the beam *vertic*al offset.

Required RF power

RF power necessary to maintain the crabbing voltage should compensate the ohmic losses in the cavity – negligible for SC cavities – and compensate the voltage induced by the beam if the beam has an offset with respect to the electric axis of the cavity. Note that the kick voltage induced by the beam may be in phase or out of phase with the crabbing voltage depending on the sign of the offset. The maximal required RF power *P* for the cavity detuned from the resonance frequency by *Δω* is (see Appendix III):

$$P = \frac{U_0^2}{4Q\left(\frac{r_\perp}{Q}\right)}\left[\left(1 + \frac{I_p Q\left(\frac{r_\perp}{Q}\right)k_0 x_0}{U_0}\right)^2 + \left(\frac{2Q\Delta\omega}{\omega_0}\right)^2\right]. \qquad \textbf{(8)}$$

Here $\omega_0 = \omega_{RF}$ is the RF frequency. The optimal external *Q* corresponding to minimal power is

$$Q_{opt} = \left[\left(\frac{1}{Q_0} + \frac{I_p\left(\frac{r_\perp}{Q}\right)k_0 x_0}{U_0}\right)^2 + \left(\frac{2\Delta\omega}{\omega_0}\right)^2\right]^{-1/2}, \qquad \textbf{(9)}$$

where Q_0 is the cavity unloaded quality factor. For the SRF cavity one can use simplified estimation for the loaded *Q*:

$$Q \approx \left[\left(\frac{I_p\left(\frac{r_\perp}{Q}\right)k_0 x_0}{U_0}\right)^2 + \left(\frac{2\Delta\omega}{\omega_0}\right)^2\right]^{-1/2}. \qquad \textbf{(10)}$$

Requirements for ILC

For the current version of ILC collider we have

Beam energy	U = 250 GeV and $\gamma = 5\times10^5$
Pulsed beam current	I_p = 5.8 mA
Pulse width	t_p = 727 µs
Repetition rate	f_r = 5 Hz
Average beam current	I_{av} = 20 µA
Vertical β function at the cavity position	β = 5 m (? should be specified)
Horizontal β function at the cavity position	β = 5 m (? should be specified)
Bunch charge	q = 3.2 nC
Crab cavity kick voltage	U_0= 0.6 MV (3.9 GHz) or 0.9 MV (2.6 GHz)
The bunch length	σ_z= 300 µm
Normalized vertical emittance	ε = 35 nm
Normalized horizontal emittance	ε = 10 µm

Requirements for ILC

Suppose the HOM electric axis offset with respect to the beam is 1 mm.
In this case, to avoid distortion of the crab voltage kick distribution along the bunch, one has for the *horizontal* shunt impedance of the "most dangerous mode":

$$r_{\perp} \ll \frac{U_0 \frac{\sigma_z \omega_{RF}}{c}}{k_0 x_0 I_p} = \frac{U_0 \sigma_z f_{RF}}{f_{HOM} x_0 I_p} \quad \text{and} \qquad (11)$$

$$r_{\perp} f_{HOM} \ll \frac{U_0 \sigma_z f_{RF}}{x_0 I_p} = 0.12 \text{ GOhm·GHz}. \qquad (12)$$

To exclude the HOM influence on the *vertical* emittance, one should have

$$r_{\perp} \ll \frac{U}{k_0 x_0 I_p} \sqrt{\frac{\varepsilon}{\gamma \beta}} \quad \text{and} \qquad (13)$$

$$r_{\perp} f_{HOM} \ll \frac{Uc}{2\pi x_0 I_p} \sqrt{\frac{\varepsilon}{\gamma \beta}} = 0.24 \text{ GOhm·GHz}. \qquad (14)$$

To exclude the HOM influence on the *horizontal* emittance, one should have

$$r_{\perp} f_{HOM} \ll \frac{Uc}{2\pi x_0 I_p} \sqrt{\frac{\varepsilon}{\gamma \beta}} = 4.1 \text{ GOhm·GHz} \gg 0.12 \text{ GOhm·GHz} \qquad (15)$$

necessary to avoid distortion of the crabbing voltage.

Requirements for ILC

The horizontal kick factor necessary to avoid the crabbing voltage distortion should be

$k_{\perp} \ll \frac{U_0}{q x_0 \sigma_z \omega_{RF}/c}$ **= 1.7×10^7 V/pC/m**

The kick factor necessary to avoid *horizontal* emittance dilution should be

$k_{\perp} \ll \frac{U}{q x_0}\sqrt{\frac{\varepsilon}{\gamma\beta}}$ **= 1.6×10^5 V/pC/m**

The kick factor necessary to avoid *vertical* emittance dilution should be

$k_{\perp} \ll \frac{U}{q x_0}\sqrt{\frac{\varepsilon}{\gamma\beta}}$ **= 9.4×10^3 V/pC/m**

Typically for the cavities operating at 1-5 GHz the kick factor has the order of < 10^3 V/pC/m. It means that single-bunch effects are not a problem.

QMIR For ANL SPX Project, 2.815 GHz, 2 MV Kick

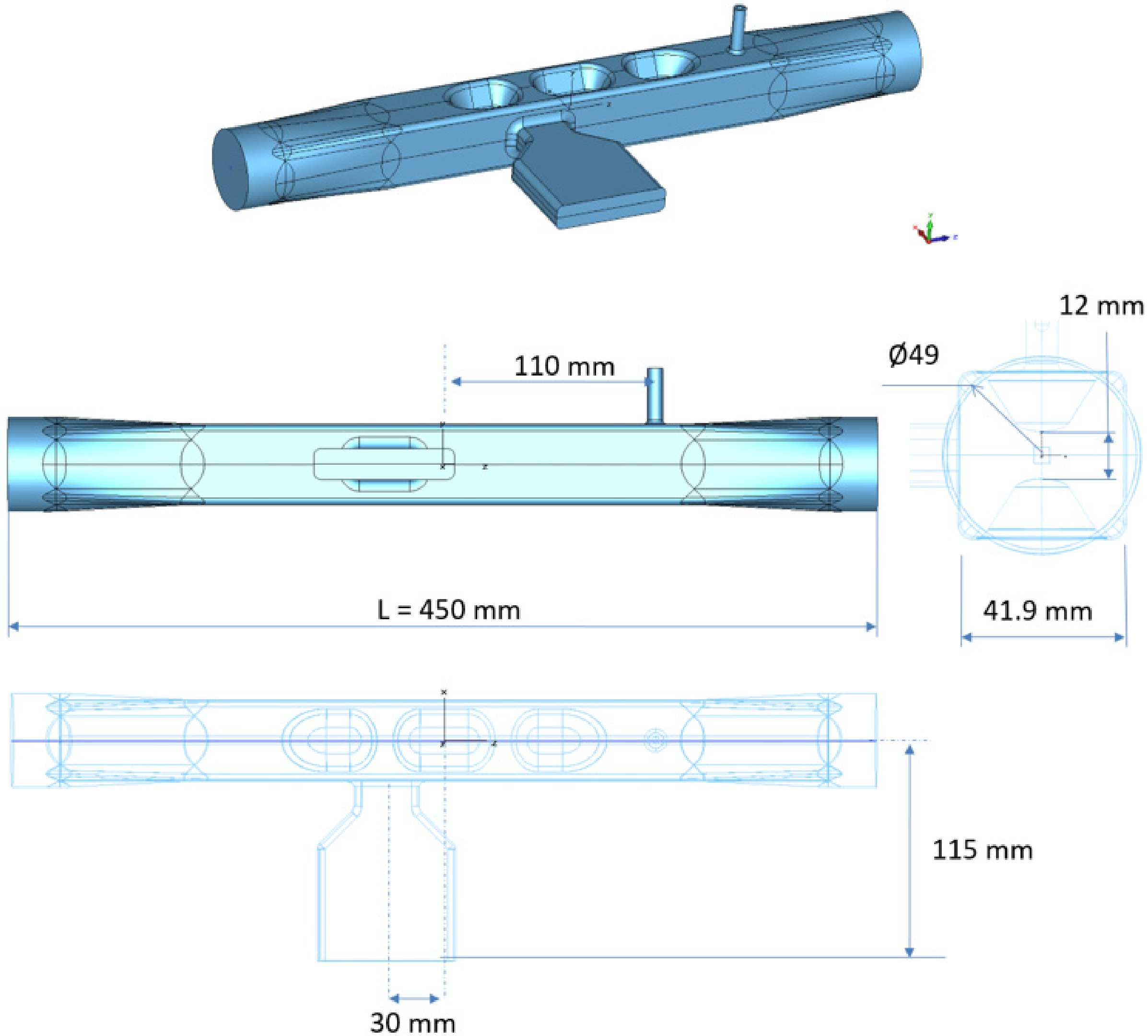
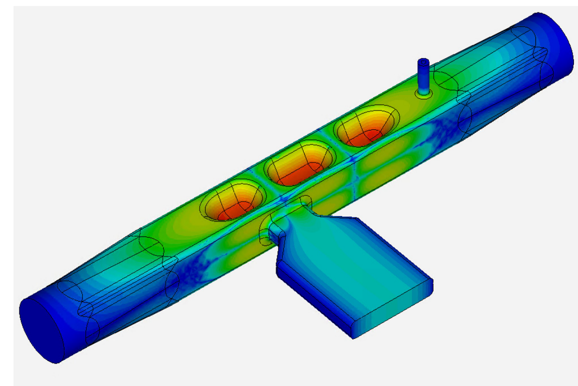
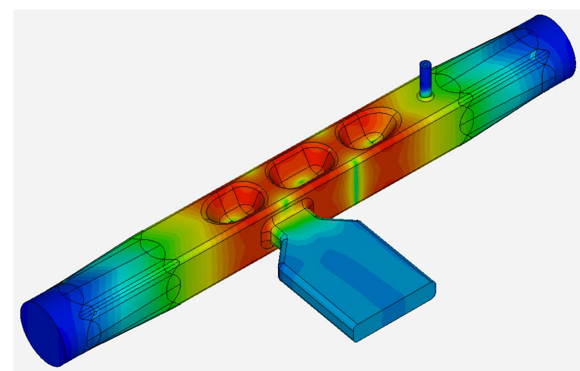


Figure 1. The 2.815 GHz three-cell deflecting cavity for the ANL SPX project.¶

$B_s \leq 75$ mT

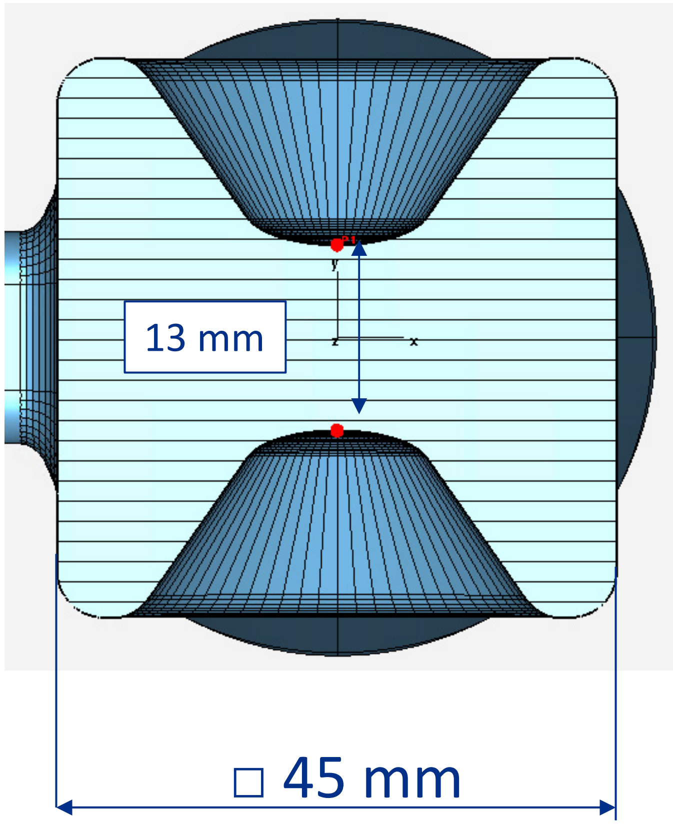


$E_s \leq 54$ MV/m

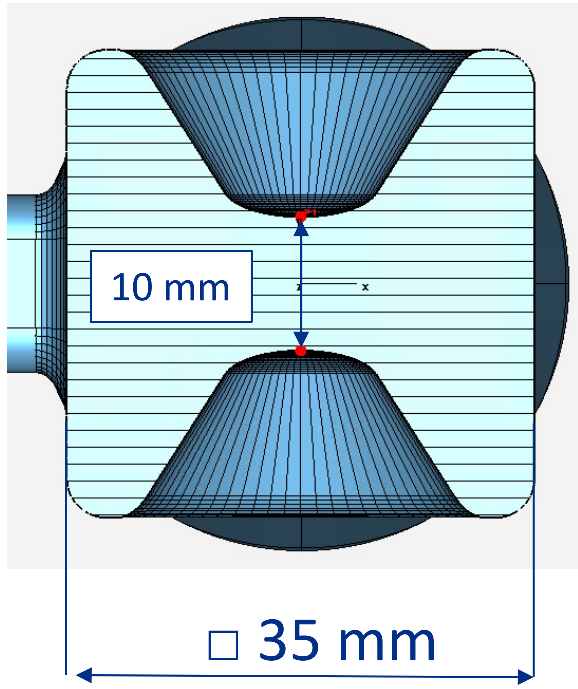


Modification of QMiR for ILC Crab Cavity

Variant A (2.6 GHz)

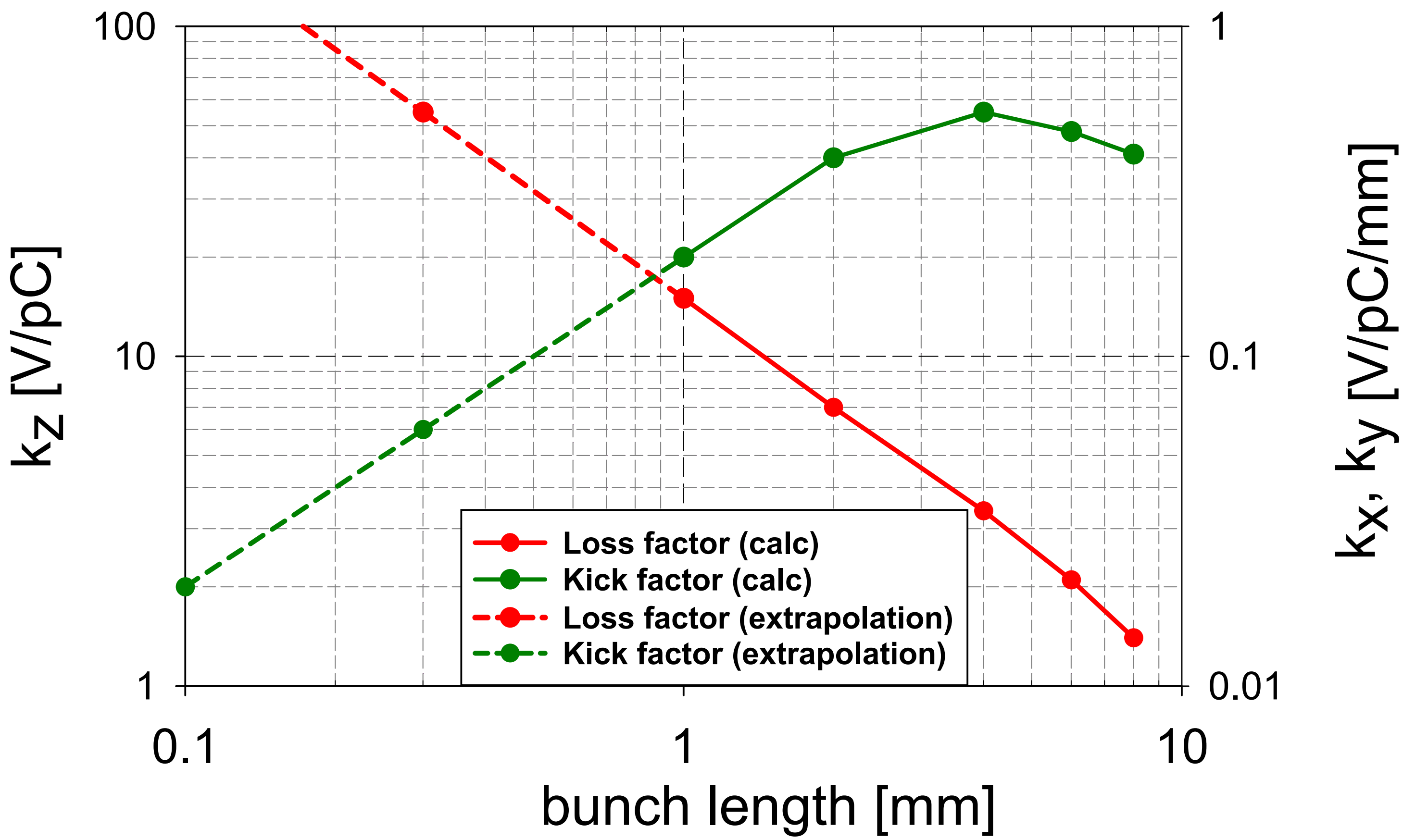


Variant B (3.9 GHz)



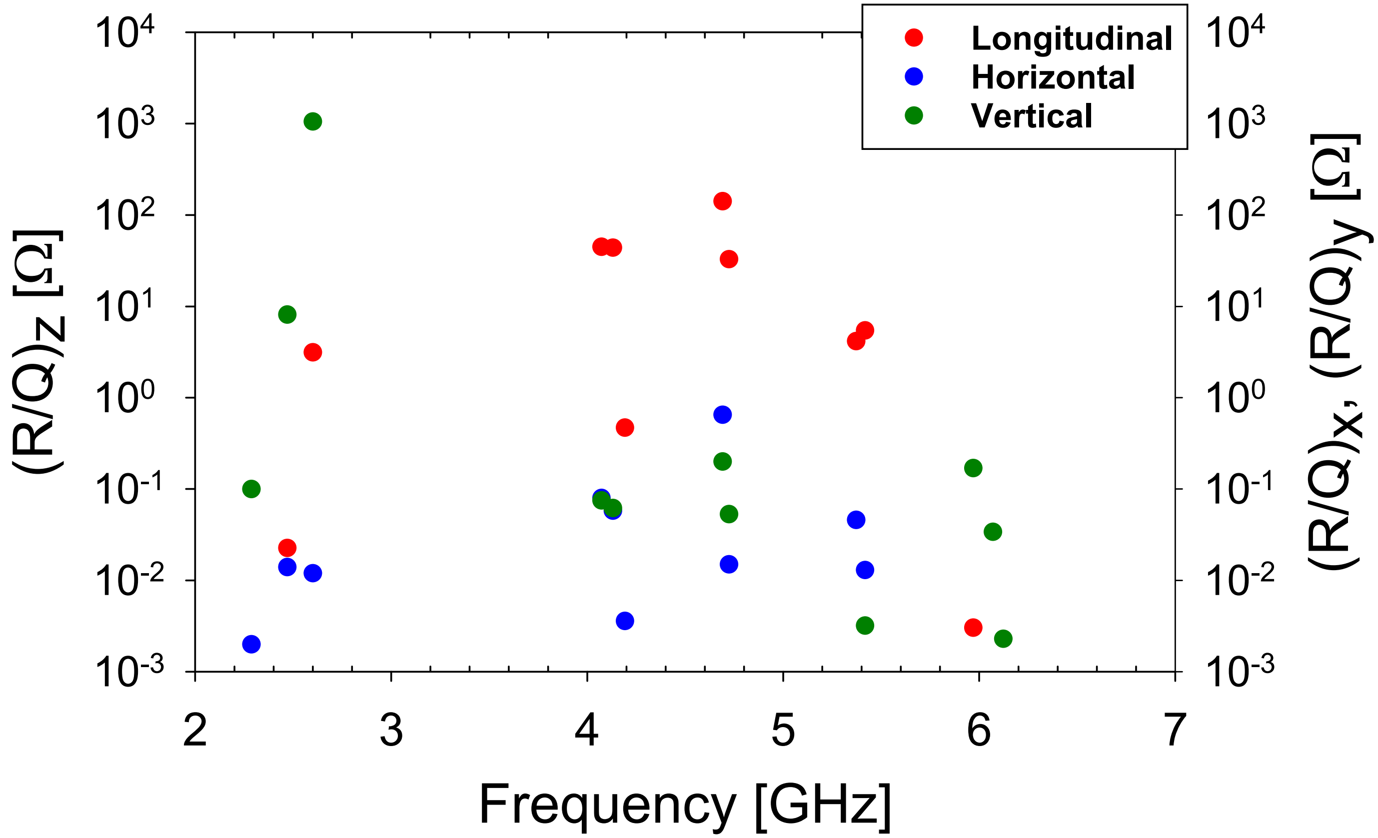
Variant A is preferable due to the larger aperture (lower beam loss)

QMiR Variant A for ILC Crab Cavity



For the ILC bunch length (0.3 mm rms), the loss and kick factors:
k_loss <= 50 V/pC and k_kick <= 0.1 V/pC/mm

QMiR Variant A for ILC Crab Cavity

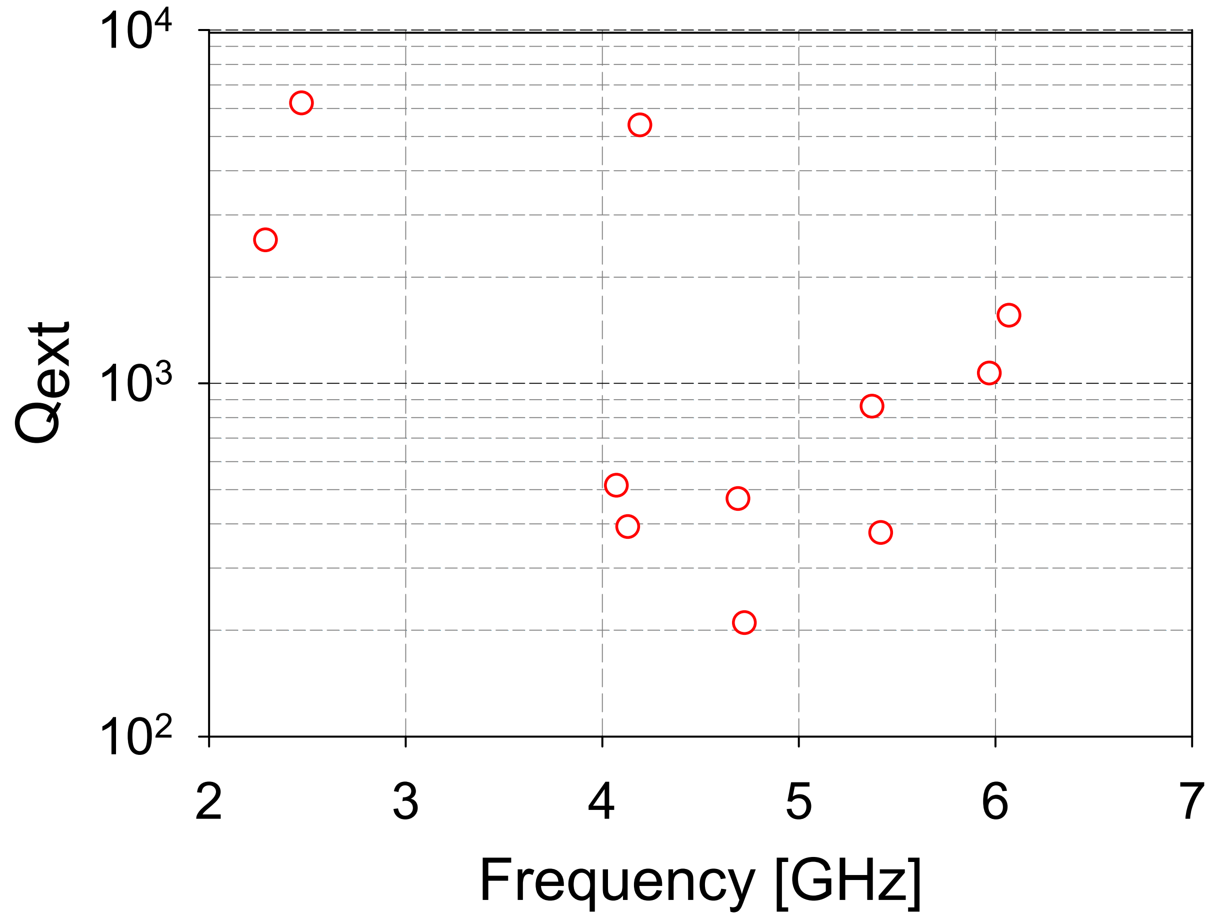


HOMs Longitudinal and Transverse* impedances :
(R/Q)z <= 100 Ω, (R/Q)x <= 1 Ω and (R/Q)y <= 10 Ω

* @1mm offset

Fermilab

QMiR Variant A for ILC Crab Cavity



Calculated HOMs external couplings: Qext < 10^4

QMIR Variant A for ILC

For QMIR cavity scaled from 2.8 GHz to 2.6 GHz one has:

Operation mode $\left(\frac{r_\perp}{Q}\right) =$ **1040 Ohm (2.6 GHz)**

Maximal dipole *horizontal* HOM $\left(\frac{r_\perp}{Q}\right) =$ **10 Ohm (2.47 GHz); Q < 1×10^4.**

Maximal dipole *vertical* HOM $\left(\frac{r_\perp}{Q}\right) =$ **1 Ohm (4.7 GHz); Q < 1×10^4.**

Horizontal kick factor $k_\perp$ **= 100 V/pC/m – no problem**

Vertical kick factor $k_\perp$ **= 10 V/pC/m – no problem**

We have requirement for *horizontal* shunt impedance:

$r_\perp f_{HOM} \ll$ **0.12 GOhm·GHz**

or $r_\perp$ << 48 MOhm. It means that for this mode Q << 5×10^6. QMIR has Q < 1×10^4

A QMIR cavity well satisfies the horizontal HOM impedance requirement.

We have requirement for *vertical* shunt impedance:

$r_\perp f_{HOM} \ll$ **0.24 GOhm·GHz**

or $r_\perp$ << 51 MOhm. It means that for this mode Q << 5×10^6. QMIR has Q < 1×10^4.

A QMIR cavity well satisfies the vertical HOM impedance requirement.

QMIR Variant A for ILC

Power requirements

Suppose we have max beam offset x_0 < 1 mm and Δf < 1 kHz (LFD, microphonics). Based Eqs (8-10) on slide #8 we can estimate:

Beam OFF: $P_{min} \approx 200$ W

Optimal Coupling: $Q_L \approx 1\text{x}10^6$

Beam ON & Microphonics: $P_{max} \approx 500$ W

Required RF power from the generator:

$P_{gen} = P_{max}$ + (overhead of 100%) ≈ < 1 kW

Summary

From physics point of view, it makes sense to put the following parameters into specification for the ILC crab cavity:

- *Horizontal* kick voltage $U_0 f_{RF} = 2.4$ MV·GHz
- Requirement for *horizontal* HOM impedance

$$r_\perp f_{HOM} \ll \frac{U_0 \sigma_z f_{RF}}{x_0 I_p} = 0.12 \text{ GOhm·GHz}$$

- Requirement for *vertical* HOM impedance

$$r_\perp f_{HOM} \ll \frac{Uc}{2\pi x_0 I_p}\sqrt{\frac{\varepsilon}{\gamma\beta}} = 0.24 \text{ GOhm·GHz}$$

- The cavity kick factors – vertical and horizontal are not critical
- Input pulsed RF power depends on the cavity design and may be specified < 2 kW
- Beam offset with respect to the cavity axis < 1 mm
- HOM electric axis offset with respect to the cavity axis < 1 mm